Factors that influence vessel biofouling and its prevention and management

Final report for CEBRA Project 190803

Edith Arndt[1], Andrew Robinson[1], Susie Hester[1,2]

Contributions from:

Bartholomew Woodham[3]
Peter Wilkinson[3]
Sonia Gorgula[3]
Bianca Brooks[3]

[1]CEBRA, The University of Melbourne

[2]UNE Business School, University of New England

[3]Department of Agriculture, Water and the Environment

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1 Summary

The Department of Agriculture, Water and the Environment (the department) leads the effective management of biofouling risk by minimising the likelihood of entry and establishment of exotic marine species transferred by vessel biofouling. Biofouling on internationally plying vessels is a significant vector for the translocation of exotic marine species (Molnar et al. 2008; Davidson et al. 2018). These species may become invasive and cause significant impact to the economy, environment and the way of life in regions where they establish. More than 250 exotic marine species have already been introduced to Australia (MESA 2019a).

International ship movements have facilitated the translocation of multiple species and often entire assemblages of tens to hundreds of species between disparate bioregions (Hewitt et al. 2011). All vessels have some degree of biofouling, even those which may have been recently cleaned or had a new application of an anti-fouling system. The biofouling process begins within the first few hours of a ship's immersion in seawater and is a continual process that is influenced by both environmental conditions (e.g. salinity, temperature) and the unique operational profile of a vessel. The development and maintenance of ship-specific documents that (i) detail the planning of biofouling management measures in biofouling management plans and that (ii) record the implemented actions in record books is the internationally accepted best-practice approach to reducing biosecurity risks associated with biofouling (IMO 2011). Maintaining low fouling levels provides economic benefits such as fuel savings and an associated reduction in greenhouse gas emissions (Abbott et al. 2000; Selim et al. 2017). It also reduces the likelihood of encountering an exotic marine species that can become invasive and cause harm (Bell et al. 2011).

A recent Australian review of national marine pest biosecurity (DAWR 2015) recommended the Australian Government "develop regulations to reduce to an acceptable level the biosecurity risks associated with biofouling on all vessels arriving in Australia". Based on this recommendation, the department is developing new biofouling requirements for vessels to implement vessel-specific biofouling management practices.

Vessels arriving into Australia pose varying degrees of biosecurity risk associated with biofouling and the assessment of that risk is complex, often occurring on a case-by-case basis. A comprehensive synopsis of the factors that contribute to biofouling risk is necessary to inform regulatory intervention. This document describes the range of factors that influence the accumulation of biofouling on vessels and how this relates to the biosecurity risk associated with biofouling.

2 Purpose of this document

This document aims to describe the current scientific and technical understanding of the factors that influence biofouling and biofouling management on all vessel types, including commercial and recreational vessels. It has been developed to inform and support the department's policy on biofouling of international vessels entering Australian territory under the *Biosecurity Act 2015* (the Act). This document does not assign risk to particular vessel scenarios but is intended to be a resource that the department can use to support an assessment of the biosecurity risk associated with biofouling under the Act. It is a living document that will be periodically reviewed and updated as new information becomes available.

3 Introduction to biofouling as a biosecurity risk

Marine biofouling is the accumulation of aquatic organisms such as microorganisms, plants, and animals on surfaces and structures immersed in or exposed to the aquatic environment (IMO 2011). It can lead to the transport of sessile organisms (e.g. mussels, clams, fanworms) that attach to hard surfaces on vessels, subsequently establish at new locations and become marine pests (Barry et al. 2015). Mobile species can also be transported as biofouling (e.g. crabs), as part of sessile biofouling matrices or within niche areas, which are heterogenous surfaces that protrude or are recessed from the hull. Niche areas include rudders, propellers, shafts, grates, struts, dry-docking support strips and other equipment that typically do not experience regular laminar flow over their surface. They are more susceptible to biofouling accumulation due to different factors and therefore often heavily fouled (Coutts & Dodgshun 2007).

Exotic marine species have to overcome a sequence of events before they are truly established. First, they have to successfully colonise vectors, survive the transport, and be released from the vectors. In the new recipient environment, they have to survive vector processes and management and endure the local environmental conditions. Successful colonisation, long-term establishment and further spread of translocated species depend on suitable habitat (Lewis & Coutts 2009; Hewitt et al. 2011). The species invasion process is outlined in Figure 1.

Many terms are used interchangeably to refer to organisms that have been introduced, by accident or intentionally, to an area outside their historic geographic ranges; including pest, non-endemic, exotic, alien, nuisance, non-native, non-indigenous or invasive species (Copp et al. 2005; AMSA 2007). Marine species that are introduced to an area beyond their native range do not always establish, spread and cause impacts. Invasiveness implies that species spread after introduction and that they have an adverse impact on biodiversity, the economy, human health, and recreational, social and cultural values (Copp et al. 2005; Bell et al. 2011; EU 2014; Georgiades et al. 2020). To avoid doubt, this report uses the following terminology:

- ‘exotic marine species’ – a species not known to be native to Australia;
- ‘introduced marine species’ – a species not native to Australia that is found in Australia as a result of human activity, whether by accidental or intentional release, escape, dissemination or placement; and
- ‘invasive marine species’ – an introduced marine species that causes, or is likely to cause, unacceptable impacts to the environment, economy, human health or social values.

Trade expansion, new trading routes, political events and climate change increase the risk of biological invasion (Minchin & Gollasch 2003; Galil et al. 2019). Exotic marine species are primarily transported around the world by anthropogenic vectors. International shipping is the main human-mediated pathway for introduction of marine species (Molnar et al. 2008; Davidson et al. 2018). This trade pathway has been growing steadily over the last decade and this trend is predicted to continue into the future (Sardain et al. 2019). For example, the annual weight of Australia’s international sea freight has been increasing since 2006-07, reaching 1.4 billion tonnes in 2015-16, with the bulk of the freight being exported to China and East Asia (BITRE 2018). Furthermore, calls to Australian ports by bulk carriers and container ships have been forecast to increase on average by 2.39% p.a. and 2.87% p.a. respectively from 2013-14 to 2029-30 (BITRE

2010). The ongoing CoVID-19 pandemic so far has not had a lasting effect on international shipping volumes. Over the first half of 2020, the number of ships arriving from China was reduced but shipping calls had already returned to normal levels in the second quarter of 2020 (DITRDC 2020). Trade politics under strained Australia-China relations, however, may influence the future predictions of shipping volumes.

Decision makers are concerned about the biosecurity risks posed by biofouling because the establishment and spread of invasive marine species could have a severe impact on Australia's environment, economy and society (Bax et al. 2003; Hayes & Sliwa 2003; Hayes et al. 2005; DAWR 2015; Fofonoff et al. 2019; Galil et al. 2019; MESA 2019b). Aggressive invasion of natural habitats by exotic species leads to changes in biodiversity and food webs of marine habitats, to erosion of physical habitat structures and, on a species level, to alteration of demographic parameters and species competition (Grosholz 2002; Fofonoff et al. 2019). In contrast to terrestrial invasive species (for example, Hoffmann & Broadhurst 2016), the economic impacts of invasive marine species in Australia are not well known or understood (Arthur et al. 2015, but see Summerson et al. 2018). Lovell et al. (2006) suggest that the costs to the economy are substantial based on a review of theoretical and empirical studies in the US. Economic costs arise from having to manage the detrimental impacts of invasive marine species on fisheries, aquaculture operations and equipment, boating, tourism and the erosion of harbour facilities and marsh banks (Lovell et al. 2006; Fofonoff et al. 2019; MESA 2019b). Negative impacts on human health can eventuate when humans consume seafood containing toxins that were introduced into the food chain by microscopic algae and dinoflagellates (Scholin et al. 2000; Hayes et al. 2005). Toxins can bioaccumulate and lead to gastrointestinal disorders and poisoning in humans (Nunes & Van den Bergh 2004; Hayes et al. 2005). Some algal species are also known to create algal blooms that can cause skin irritations in humans on direct contact (Nunes & Van den Bergh 2004).

Among shipping-related mechanisms associated with the risk of spreading exotic marine species, ballast water (i.e., water pumped into vessels to maintain stability and structural integrity) has historically received the most attention from regulators (Hillman et al. 2004; IMO 2004; MPI 2005; IMO 2019). This focus is now shifting to biofouling (Georgiades et al. 2020). Biofouling is a phenomenon that has impacted sea farers for centuries. In recent decades, there has been a re-emergence of research on the topic and a new focus on vector management. Early indications of the importance of biofouling as a vector for the introduction of exotic marine species (e.g. Cranfield et al. 1998; Gollasch 2002; Lewis 2002; Godwin 2003) were followed by calls for more data collection (Davidson et al. 2009) and then, based on the analysis of large datasets, concerns raised that biofouling may be an even more important mechanism than ballast water for introducing exotic species (Hewitt & Campbell 2010; Williams et al. 2013). Vessel biofouling is reportedly responsible for introducing and translocating about 58% of the currently recognised non-indigenous (i.e., introduced or cryptogenic) marine species in Australia, surpassing the risk of introduction by ballast water which is reportedly responsible for only 22% (global dataset, Hewitt & Campbell 2010). Vessel biofouling and ballast water were ranked highest among vectors for translocating and introducing non-indigenous marine species, in all three datasets used in this study (Hewitt & Campbell 2010). The International Maritime Organization (IMO) formally discussed biofouling-mediated transfer of invasive marine species for the first time in 2006 (IMO 2021). It now recognises biofouling as a potentially significant vector for the transfer of invasive aquatic species (IMO 2011).

The IMO's Marine Environment Protection Committee (MEPC) developed the *Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species* (IMO 2011) (the guidelines) for best-practice management of biofouling. The guidelines stipulate that vessel owners should have a biofouling management plan for each vessel and keep a biofouling record book for documenting all biofouling management activities and inspections related to that vessel (IMO 2011). IMO (2012) also provides guidance on how to minimise biofouling for owners of recreational craft, aiming to prevent transfer of invasive aquatic species via recreational boats.

More recently, New Zealand and California have developed regulations to minimise the risk of entry of invasive marine species through the vessel biofouling pathway. New Zealand's '*Craft Risk Management Standard: Biofouling on Vessels Arriving to New Zealand*' was introduced on 15 May 2014 and came into force on 15 November 2018 after a 4-year lead-in period. This standard was issued under the Biosecurity Act 1993. It defines a 'clean hull' and prescribes acceptable thresholds of biofouling for long-stay and short-stay vessels (MPI 2018a). California's State Lands Commission has enforced biofouling management regulations to minimise the transfer of nonindigenous species from vessels arriving at California ports since 1 October 2017 (CSLC 2017). In contrast to New Zealand, California's regulations do not define a clean hull standard. Both sets of regulations align with the IMO guidelines.

In Australia, the Act and the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) address the problem of invasive species. The Act provides for the implementation of activities to prevent, control and eradicate invasive pests; and the EPBC Act lists key processes that consider the detrimental impacts of invasive species but ignores exotic marine species. The Act regulates ballast water but does not include specific legislative requirements for the management of biofouling on international vessels. This means that the Australian government currently does not have regulatory requirements for international vessels to manage their biofouling prior to entering Australian waters (DAWR 2015). Instead, existing powers under the Act can be used to address biosecurity risk associated with biofouling upon a vessel's entry into Australian waters where the risk is deemed to be unacceptable. In practice, this means that vessel arrivals are currently monitored by regulators and actions can be taken on a case-by-case basis under that Act, despite the lack of specific biofouling management language at present. National management of biofouling largely consists of voluntary guidelines and a system of pest monitoring at key ports (DF 2017). Some Australian State and Territory biosecurity agencies have implemented requirements to manage biofouling in their jurisdictions, such as Western Australia and the Northern Territory (DAWR 2015; DF 2017).

The DAWR 2015 Review of National Marine Pest Biosecurity made the following recommendation in relation to biofouling:

> "The Australian Government should develop regulations to reduce to an acceptable level the biosecurity risks associated with biofouling on all vessels arriving in Australia."

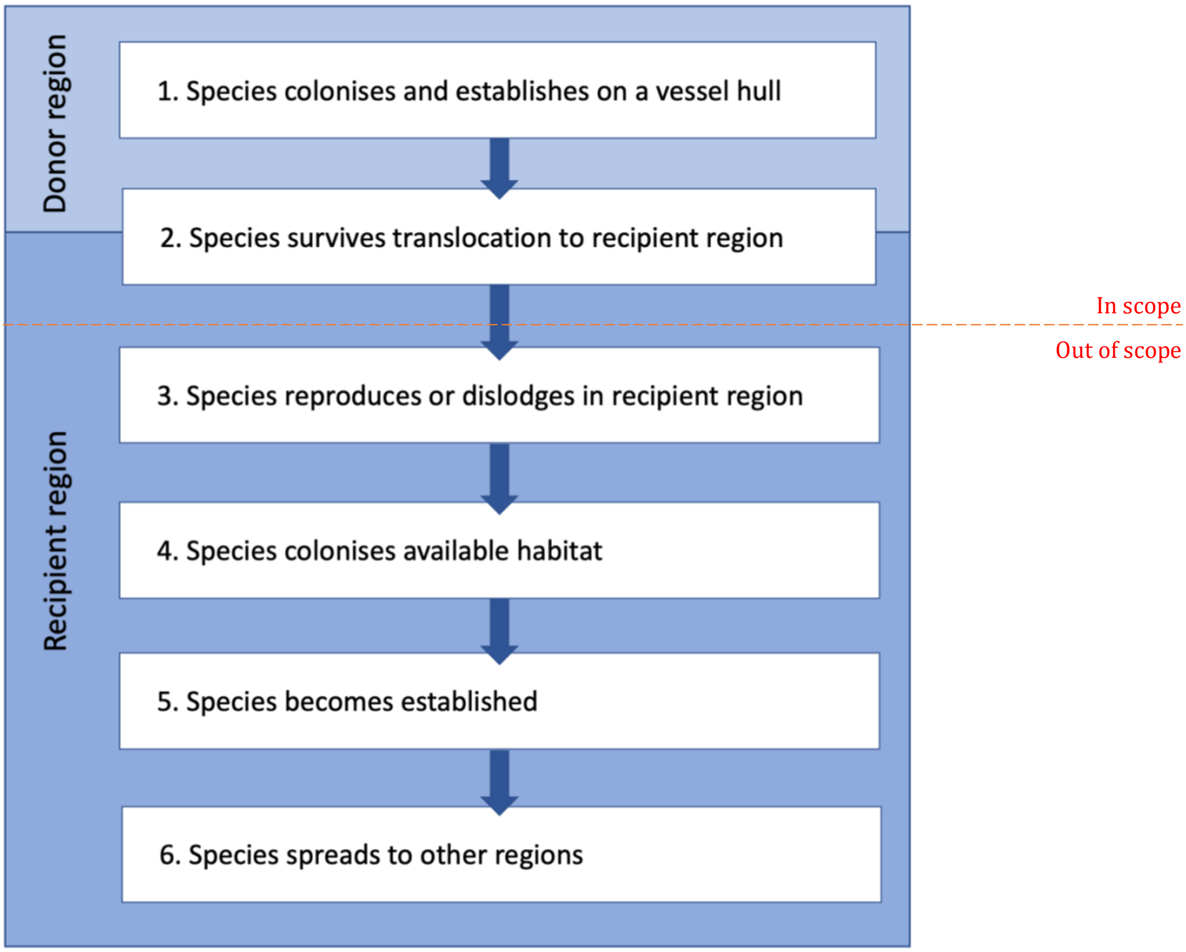
Based on this recommendation, the department is developing new biofouling requirements and released a Consultation Regulation Impact Statement in 2019 to propose a preferred policy option that includes the requirement for vessels to implement vessel-specific biofouling management practices (Hayes et al. 2019). Two key business needs of the department's preferred policy for biofouling management are:

1. The ability to rapidly and consistently assess the risk associated with a vessel's biofouling on the basis of the vessel's prior biofouling management practices; and
2. Effective communication with industry stakeholders to ensure they are aware of their risk profile, and how to achieve compliance.

4 Scope and structure of this document

The scope of this document is an evaluation of factors that influence the likelihood of biofouling organisms attaching to commercial and recreational vessels and being transported to the Australian border (Figure 1; processes above the red dotted line are in scope). Transfer, establishment or spread of marine exotic species after arrival in a recipient region are out of scope and will not be discussed.

The balance of the document is structured as follows. Chapter 5 describes the typical biofouling process that affects maritime vessels. Factors influencing the likelihood of entry of exotic marine species are discussed in chapter 6.



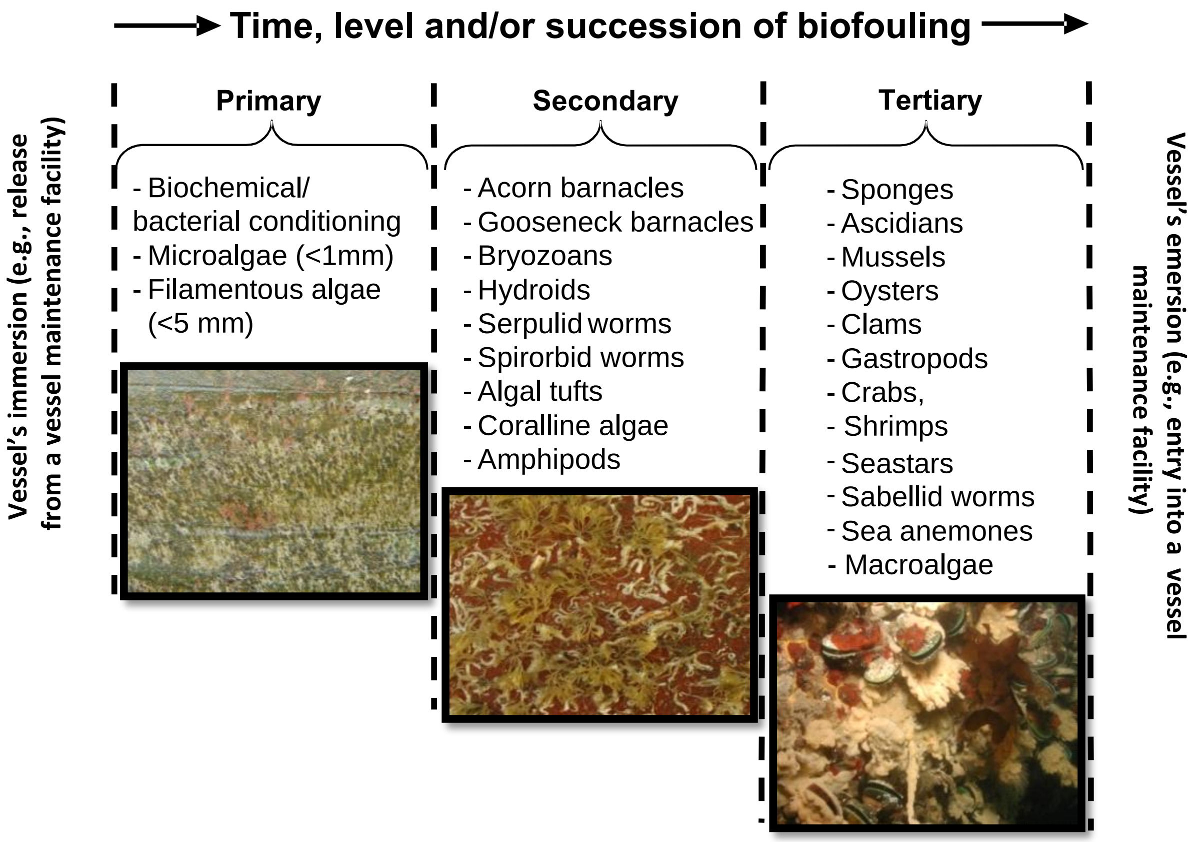
Source: Adapted from Lewis & Coutts (2009) and Hewitt et al. (2011)

Figure 1: Conceptual model of the species invasion process

5 The process of biofouling and its impacts

In general, the accumulation of a marine fouling community is a complex process (Aldred & Clare 2008). For simplicity and practical reasons, biofouling succession has been divided into three key categories: primary, secondary, and tertiary levels of biofouling (Figure 2; Abarzua & Jakubowski 1995; Coutts & Taylor 2004; Floerl et al. 2005a; URS 2007). It is important to note that biofouling succession is a dynamic process that involves shifts in the micro- and macrofouling communities over time (Raeid et al. 2019). Consequently, the three categories tend to overlap (Abarzua & Jakubowski 1995).

The first stage of biofouling succession is the formation of a thin mucilaginous layer of organic and mineral like deposits. It commences immediately after submersion of a hard surface into seawater (Wahl 1989; Raeid et al. 2019). This biochemical conditioning is rapidly colonised, first by bacteria, then by microalgae such as diatoms, protozoa, cyanobacteria and pluricellular organisms which create a thin biofilm, also referred to as slime layer or 'microfouling' (Wahl 1989; Lewis 1998; Railkin 2004; URS 2007; Dobretsov 2009; IMO 2011; Dobretsov et al. 2013; Georgiades & Kluza 2014).



Source: published in Coutts et al. (2010c) as a modified version from the Department of Agriculture, Fisheries and Forestry (2009)

Figure 2: Temporal succession of vessel biofouling

Biofilms provide a suitable, but not necessarily mandatory, substrate for the attachment or growth of microorganisms and the settlement of secondary biofouling organisms, which tend to be the most dominant and frequently encountered biofouling organisms on vessel hulls. Depending on the composition of the biofilm, the release of particular substances by marine bacteria can inhibit the attachment and growth of microorganisms and the settlement of secondary biofouling species such as invertebrate larvae and algal spores (Dobretsov et al. 2006).

The second and third stages of succession involve colonisation of the biofilm by macrofouling organisms such as invertebrate larvae and macroalgal spores (Wahl 1989). Secondary fouling usually includes hard encrusting animals such as acorn barnacles, bryozoans and serpulid worms, but may also include soft algal tufts and mobile amphipods (Coutts & Taylor 2004; URS 2007). Tertiary fouling generally consists of larger organisms, such as sponges, solitary and compound sea squirts, mussels, oysters and seaweeds. Mobile animals such as crabs and sea stars are able to live within this tertiary growth (Coutts & Taylor 2004; URS 2007). Barnacles and serpulid tubeworms are species that are encountered often on fouled vessels (Davidson et al. 2009) because they overcome the selection pressure of vessel movement by being robust to hydrodynamic forces (Coutts & Taylor 2004).

On vessels, when anti-fouling systems are absent, old, worn, excessively dried out or otherwise damaged, fouling succession in most port and coastal waters generally follows the temporal pattern outlined below (URS 2007):

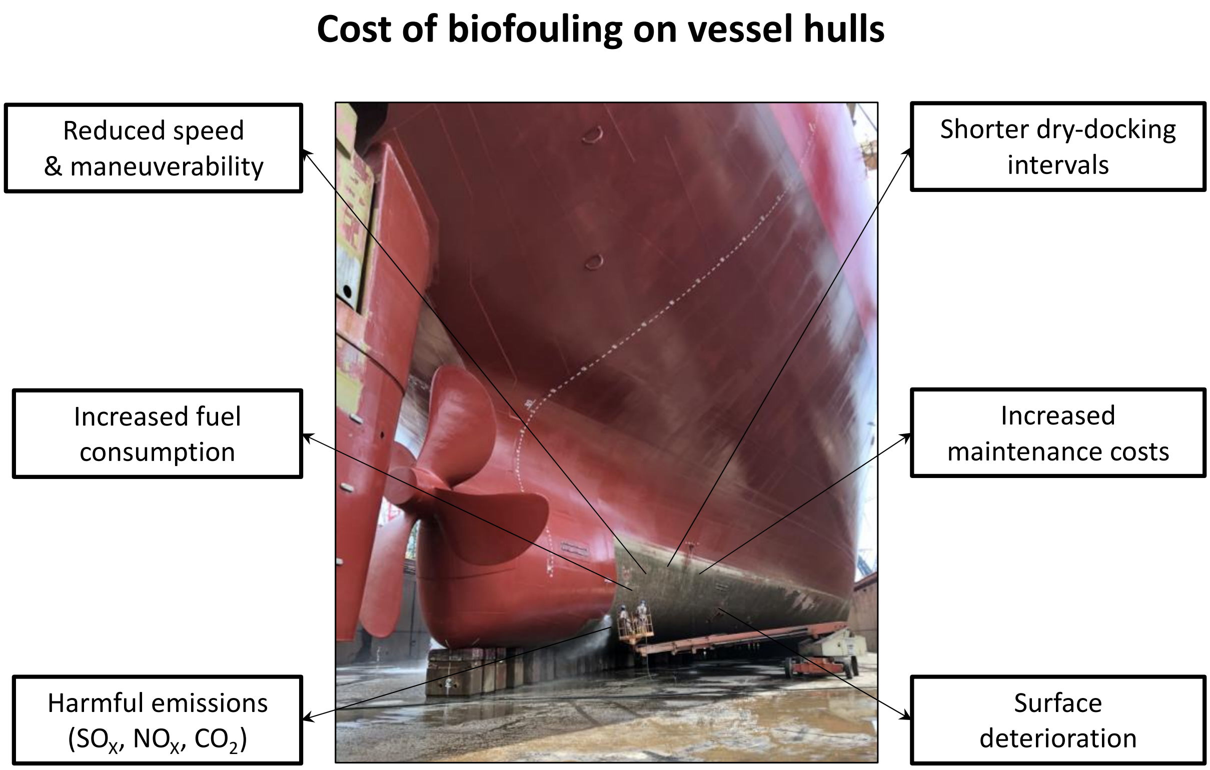
- primary slime layer with grey and green tinges that vary with diatom content and light;
- gossamer-like amphipod tubes (dependent on season and level of water movement);
- filamentous green algae that can develop into waterline or transom beards providing shelter to amphipods and other clinging biota;
- encrusting bryozoans;
- tubeworms, barnacles, turfing red algae, hydroids, erect bryozoans, and ectocarpoid brown algae;
- mussels, oysters, encrusting sponges, sea anemones and sea squirts; and
- larger mobile forms, including errant polychaetes, crabs, whelks, nudibranchs, crinoids, and territorial fishes.

5.1 Impacts of biofouling on vessel performance and economy

Biofouling on the hull causes significant economic costs to the shipping industry by increasing hydrodynamic resistance, affecting manoeuvrability and reducing speed by up to 50% (Selim et al. 2017; Anisimov et al. 2019). Fouling within internal seawater systems, such as heat exchangers and cooling systems may restrict flow and reduce efficiency (Galil et al. 2019). Frictional drag increases fuel costs and atmospheric emissions (Hewitt et al. 2007; Schultz 2007; Edyvean 2009; Galil et al. 2019). For example, to maintain normal vessel speed, fuel consumption on a vessel without an appropriate antifouling coating may increase by 40% (Dahlbäck et al. 2010). Even the presence of biofilm alone may be able to change total resistance (Schultz et al. 2011) and increase fuel consumption and decrease vessel speed as investigated in a study using simulation models (Farkas et al. 2020). Biofilms can also develop in internal pipes under heavy fouling pressure, when passive protection through CuNi piping cannot prevent copper tolerant bacteria from colonising, causing microbial induced corrosion of CuNi pipes, or when microbes become resistant to non-oxidising biocides (Cloete 2003; Grandison et al. 2011). The initial biofilm may then provide favourable conditions for colonisation by macrofoulers (Grandison et al. 2011).

Biofouling may increase the frequency of vessel maintenance because biofouling needs to be removed through in-water or onshore cleaning and anti-fouling coatings may need to be renewed earlier than the planned dry-dock interval (Davidson et al. 2016).

While there is a financial incentive for the shipping industry to control biofouling on vessel hulls due to the economic cost of increased drag, there is less interest in preventing or minimising biofouling of niche areas, particularly internal niche areas. Biofouling in these areas does not affect vessel performance such as vessel speed, with the exception of fouling of propellers and DDSS. This view is reflected by the type of research industry invests in, such as the specific hydrodynamic influences of coating and biofouling topography or the efficacy of biocides and release rates (Davidson et al. 2016). Industry's focus on hull areas is in stark contrast to that of biosecurity risk managers, who see niche areas as primary areas of concern for their role in amplifying biosecurity risk (Davidson et al. 2016). However, ship operators and the coatings industry are increasingly aware of and engage with biosecurity concerns through the introduction of biofouling management guidelines and, in some parts of the world, biofouling regulations (Davidson et al. 2016; CSLC 2017; MPI 2018a).



Modified from Selim et al. (2017). Image by Biofouling Solutions Pty Ltd

Figure 3: The economic and environmental costs of biofouling on vessel hulls

6 Factors that influence biofouling

A preliminary literature review for CEBRA project 190803 – 'Updating the *Vessel Check* biofouling risk assessment framework' of peer-reviewed and grey literature identified the main factors that influence the amount of biofouling on vessels as: (i) the presence and quality of anti-fouling coatings; (ii) the location on a vessel of an area vulnerable to fouling; and (iii) vessel characteristics and travel patterns. Building on this initial assessment and broadening its focus, this chapter will use the following structure in discussing the influential factors. First, it will describe current technologies used to minimise the accumulation of biofouling, including the different types of anti-fouling coatings and their specifications and marine growth prevention systems for internal pipework. The remainder of the chapter will describe the other factors influencing vessel biofouling such as vessel characteristics and operating profile, and the suite of available biofouling management practices, divided into proactive and reactive measures. A simple model of vessel biofouling provides a visual summary of the factors that we identified (Appendix 1).

6.1 Anti-fouling technologies

Vessel operators use technologies and management practices to minimise biofouling on all submerged surfaces of vessels. Technologies can reduce biofouling to a level that is acceptable to industry in terms of operational efficiency, i.e. optimising vessel performance and reducing running and maintenance costs (Davidson et al. 2016; Galil et al. 2019).

Currently, there are no effective technologies available that prevent the formation of biofilms on ships' submerged surfaces. Marine biofilms can even develop on the surface of anti-fouling coatings that contain biocides (Dobretsov 2009) and incidental amounts of macrofouling on vessels are common, even if the best management practices are applied by vessel owners (Georgiades & Kluza 2017). The aim of anti-fouling technologies, such as coatings, is not necessarily to prevent biofilms and biofouling from developing but to delay their onset. Modern coatings are effective in doing that and many vessels can achieve inter-dry-docking periods without much or even any intervention (Davidson et al. 2016). If anti-fouling technologies are not effective in delaying the onset of biofouling for whatever reason, regular cleaning and reapplication of anti-fouling coatings is required to prevent the progression of fouling and to optimise vessel efficiency (Scianni & Georgiades 2019). In this section we summarise the anti-fouling technologies that are available to vessel operators. First, we discuss the different types of anti-fouling coatings and their features and then the systems that can be installed to prevent marine growth in internal seawater systems.

6.1.1 Anti-fouling coatings

An anti-fouling coating is a lacquer paint designed to prevent or minimise the adhesion and growth of biofouling organisms on a surface to which the paint is applied (Georgiades et al. 2018). Anti-fouling coatings reduce the likelihood of the settlement and translocation of exotic marine species. Industry is primarily concerned about the effects of biofouling on propulsion dynamics and associated costs, which has been the driver for the development of a range of modern anti-fouling coatings. These modern coatings aim to maintain a sufficient level of protection against colonisation for extended periods of time irrespective of the exposure conditions (Sánchez &

Yebra 2009). There are two main classes of anti-fouling coatings utilised by the maritime industry: **biocidal anti-fouling coatings** and **non-biocidal foul release coatings**. Both types of coating aim to delay/prevent the adhesion or the persistence of biofouling organisms on submerged surfaces. They also both need appropriate vessel speeds to perform optimally and deteriorate in effectiveness over time.

6.1.1.1 Biocidal anti-fouling coatings

Biocidal anti-fouling coatings contain toxic agents designed to prevent adhesion and growth of biofouling species. These coatings release biocides into the boundary layer of the immersed surface at a prescribed rate from where they are dispersed into the seawater (Finnie & Williams 2009; TechLaw 2017). Primary biocides include inorganic copper and secondary biocides are made of a range of other chemical components (Lewis 2020). Copper is present in the marine environment at low concentrations and an important trace element for marine organisms (Morel et al. 2004). At high concentrations, however, copper is a toxic heavy metal that adversely affects marine life, for example, reducing reproductive success and altering histology in fish, and disrupting cell division in diatoms (Hall Jr. et al. 1998). Some marine species are copper tolerant and can survive and grow when exposed to high concentrations of copper (Weiss 1947; Russel & Morris 1970; Piola & Johnston 2006; McElroy et al. 2017). The leaching rate and efficacy of the biocide determines the performance and service life of the coating (Floerl et al. 2010; Anisimov et al. 2019), but coating performance is also determined by the concentration of biocide within the paint, the amount of paint applied (dry-film thickness), the correct application, and the match between paint type and vessel operational profile (Georgiades et al. 2018).

Some fouling species can be resistant to toxic substances. For example, some fine filamentous algae are resistant to the toxic biocides contained in anti-fouling coatings (Evans 1981; Reed & Moffat 1983; Callow 1986; Lewis 2002). Therefore, modern biocidal anti-fouling coatings also use a wide range of booster biocides (also called co-biocides) which are added to achieve broader spectrum of protection against biofouling organisms and usually make up 0.1–10% of the paint formulation (Martins et al. 2018). Booster biocides are toxic. They can affect target and non-target marine species alike (Floerl et al. 2010; Dafforn et al. 2011; Martins et al. 2018). Another point of concern with antifouling marine coatings is that they use microplastics as binding agents (Shtykova et al. 2006), which have been detected in water samples off the southern coast of Korea (Song et al. 2014) and are considered to be environmentally problematic (Boucher & Friot 2017). But the use of anti-fouling paints has been controlled to mitigate risks to people and the environment (EPA NZ 2013).

Biocidal coatings are designed for a range of vessel types and their intended service activity (e.g. voyage speed and frequency of movement). The longevity of biocidal coatings varies considerably (Table 1), and some biocides are more potent against certain types of fouling organisms than others (Finnie & Williams 2009). Vessel owners and managers should seek advice from coating manufacturers to determine which type of coating best suits their vessel’s activity patterns to ensure maximum efficacy. Any deviation from the conditions the coating is designed for can reduce the effectiveness of the coating and lead to the premature accumulation of high levels of biofouling (INTERTANKO 2016; Georgiades et al. 2018).

Biocidal coatings come in a variety of types such as: (1) insoluble matrix, contact leaching; (2) soluble matrix, conventional; (3) soluble matrix, controlled depletion polymer (CDP); (4) self-polishing copolymer (SPC); (5) hybrid coatings; and (6) metallic coating systems (Table 1).

Table 1: Biocidal anti-fouling coatings

Type	Target	Longevity
Insoluble matrix, contact leaching paint	***Coatings industry:*** Power boats and regatta yachts (Hempel 2020) ***Academic literature and government reports:*** Commercial and recreational vessels, lower performance end of market (Finnie & Williams 2009; Floerl et al. 2010; Georgiades et al. 2018) Rarely used on trading vessels due to exponential decrease of biocide leaching rate (Kiil & Yebra 2009)	12 – 18 months (Chambers et al. 2006) 12 months (Finnie & Williams 2009) Rarely exceeding 18 months (Georgiades et al. 2018) 12 – 24 months for traditional insoluble matrix coatings and 24 – 36 months for modern hard type coatings (Floerl et al. 2010) Effective service life less than 24 months (Lewis 2020) Assumed lifetime of 12-24 months (Almeida et al. 2007; Lejars et al. 2012)
Soluble matrix, conventional	***Government report:*** All vessel types. Unsuitable for vessels that are dry-docked for extended periods or for vessels with high speed (Floerl et al. 2010)	12 – 15 months (Almeida et al. 2007) 18 – 24 months (Pei & Ye 2015) Commercial vessels: 48 months Recreational vessels: 24 months (Floerl et al. 2010) Service life between 18 and 36 months (Lewis 2020) Assumed lifetime of 36 months or less (Lejars et al. 2012)
Soluble matrix, controlled depletion polymer (CDP)	***Coatings industry:*** All vessel types at all speeds and in all trading conditions (Hempel 2020) ***Academic literature and government reports:*** Displacement vessels. Commercial (trawlers) and recreational vessels (cruising yachts), and fishing craft. Less suitable for high-speed vessels or tropical waters (Floerl et al. 2010)	Service life between 18 and 36 months (Lewis 2020) Lifetime of 36 months (Chambers et al. 2006) Generally limited to around 36 months (Finnie & Williams 2009) Assumed lifetime of 36 months or less (Lejars et al. 2012) Effective for up to 36 months (Pei & Ye 2015; Georgiades et al. 2018)

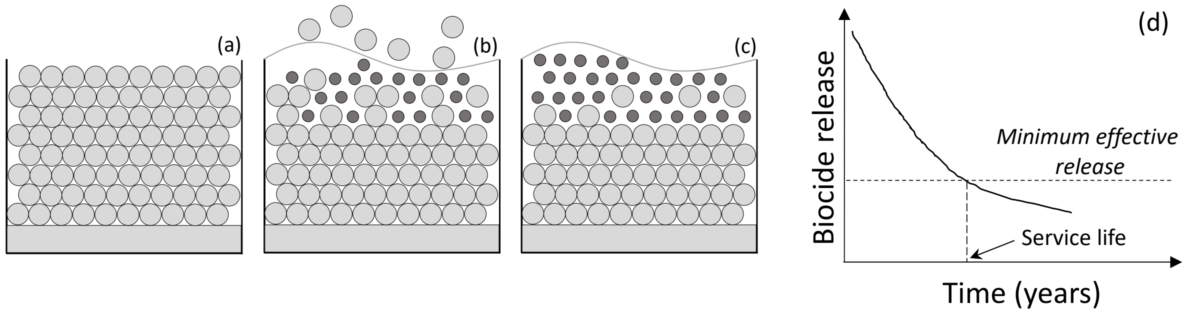
Type	Target	Longevity
	Leisure boats and small ships with relatively short service times (Almeida et al. 2007) Ablative paints are mainly associated with smaller recreational vessels (Lane et al. 2018)	Commercial vessels: 36 months Recreational vessels: 24 months (Floerl et al. 2010) Vessels with 36 months dry-docking intervals (Hellio & Yebra 2009; Kiil & Yebra 2009) Protection period longer than 36 months (Almeida et al. 2007)
Self-polishing copolymer (SPC) anti-fouling coatings. TBT[1] free.	***Coatings industry:*** Slow steaming vessels and vessels with frequent idle periods (Hempel 2020; Jotun 2020a) Vessels operating at medium to high speed and activity with short idle periods (Hempel 2020) Superyachts operating in coastal trade at low to medium speed and low to medium activity (Hempel 2020) For medium activity vessel like tankers and bulkers (Jotun 2020a) For high activity vessels like containers, liquefied natural gas and car carriers (Jotun 2020a) ***Academic literature and government reports:*** Merchant vessels (Coutts & Taylor 2004) Commercial vessels (Almeida et al. 2007) Commercial and recreational vessels. Less suitable for high-speed vessels or tropical waters (Floerl et al. 2010)	Typical service life around 36 months, but reported cases of 60 months service lives (Almeida et al. 2007) SPC paints with copper-based toxins, complemented by booster biocides have a service life of 5 years (Candries et al. 2003) Lifetime of 60 months (Chambers et al. 2006) Commercial vessels: 60 months Recreational vessels: 24 months (Floerl et al. 2010) Assumed lifetime of 60 months (Lejars et al. 2012) Effective for up to 60 months (Georgiades et al. 2018) Dry-docking intervals of up to 90 months with some Hempel Globic SPC paints, using nanocapsule technology (Hempel 2020) Up to 90 months proven performance (Jotun 2020a) Service life of up to 90 months (Lewis 2020)
CDP/SPC hybrid coatings	Target market the same as for CDP and SPC	Effective for 36 – 60 months (Finnie & Williams 2009; Lejars et al. 2012)
Metallic coating systems	***Government report:*** Offshore and fixed installations (Georgiades et al. 2018)	Up to 20 years (Georgiades et al. 2018)

[1] Tributyltin (TBT) is an organotin anti-fouling compound that was used as a biocide in anti-fouling coatings. It was banned on 1 January 2008 due to its toxic effects on marine communities (Lewis 1998; Dafforn et al. 2011).

Type	Target	Longevity
*Enzyme-based coatings	***Academic literature:*** Yachts (Lejars et al. 2012)	Unknown (Lejars et al. 2012)

*Listed in this table because enzymes used for direct enzymatic anti-fouling can be biocidal

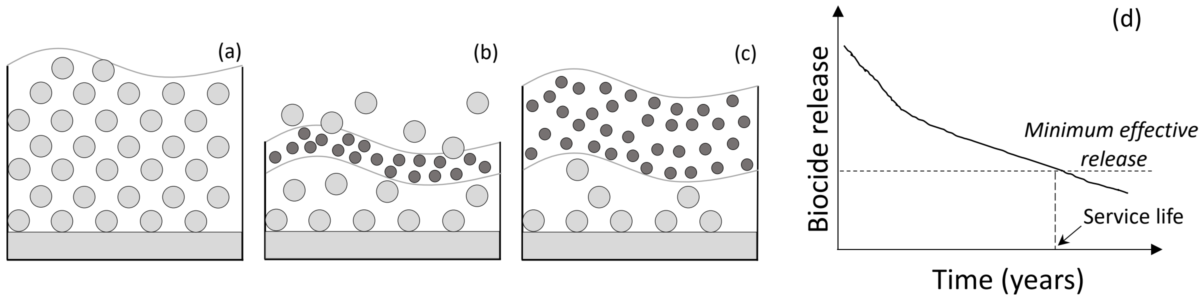
Insoluble matrix contact leaching coatings contain a mechanically robust and durable film forming material (binder) that is combined with as much pigmentous biocide (typically cuprous oxide) as possible (Finnie & Williams 2009). The freshly painted surface contains biocide particles (Figure 4a, light grey circles). When the paint film is exposed to seawater, biocide particles dissolve from the film-seawater interface, creating pores in the film. Pores fill with water and expose further biocide particles (Figure 4b, dark grey circles represent the pores in the matrix). This process progresses deeper into the paint film and the flux of biocide decreases exponentially with time (Finnie & Williams 2009; Kiil & Yebra 2009) as the diffusion path of biocide particles to the paint surface increases (Figure 4c, Kiil & Yebra 2009; Zhao & Wang 2015; Lewis 2020). Release of biocides is usually non-uniform, with high initial release rates followed by a sharp reduction over time (Figure 4d, Georgiades et al. 2018).



Modified from Anisimov et al. (2019) and Bressy et al. (2009)

Figure 4: Insoluble matrix, contact leaching paint.
Light grey circles represent biocide particles and dark grey circles represent the pores in the matrix.

Soluble matrix coatings are paints designed to release biocides at a constant rate until the paints have completely dissolved (Kiil & Yebra 2009). *Conventional soluble matrix paints* contain a binder that is slightly soluble in water (Figure 5a). The most commonly used soluble binder component is rosin or a derivative of it (Finnie & Williams 2009). Hydration slowly dissolves the coating surface, releasing the freely associated biocide (Georgiades et al. 2018). This type of soluble matrix coating system is called ablative or erodible because the dissolution of the binder component leads to thinning of paint film over time (Figure 5b, Finnie & Williams 2009; Kiil & Yebra 2009). The rosin facilitates surface polishing which aims to maintain diffusion path lengths, i.e., the distance between the dissolving biocide particles and the paint surface. However, the leaching rate of biocides is often too fast and uncontrolled (Kiil & Yebra 2009). Further, the formation of insoluble copper carbonate fouling of the matrix can prevent the release of biocide particles (Anisimov et al. 2019). The build-up of the leached layer can be seen in Figure 5c (dark grey circles) and the drop in the release rate of the biocide in Figure 5d. The leached layer is the porous, Cu_2O depleted binder matrix, that fills with seawater (Kiil & Yebra 2009). It is mechanically weak and partially removed by water flow, but over time the thickness of the leached layer can increase and lead to inefficient polishing action, premature failure and less controlled biocide release (Lewis 1998, 2020).



Modified from Anisimov et al. (2019) and Bressy et al. (2009)

Figure 5: Soluble matrix, non-leaching matrix coating system.
Light grey circles represent biocide particles and dark grey circles represent the leached layer in the uppermost layer of the coating.

The binders of conventional soluble matrix paints are sensitive to atmospheric oxidation and require fast re-floating after dry-docking (Lewis 1998; Yebra et al. 2004). The activity of biocidal particles is also weak under stationary conditions which makes this type of paint unsuitable for slow speed vessels or vessels that remain inactive for long periods (Yebra et al. 2004; Floerl et al. 2010). High vessel speed, on the other hand, can erode the matrix too quickly, compromising the effectiveness of the anti-fouling coating (Floerl et al. 2010).

Controlled depletion polymer (CDP) coating systems are the more modern version of conventional soluble matrix paints and their working mechanisms are assumed to be similar (Almeida et al. 2007). CDPs control the dissolution rate of the matrix better than conventional soluble matrix paints by using a combination of polymeric ingredients with seawater-soluble binders (Almeida et al. 2007; Finnie & Williams 2009; Georgiades et al. 2018). The ingredients controlling the dissolution process allow the biocides and the soluble binder to be washed from the surface in a constant ablation/erosion rate (Almeida et al. 2007). Disadvantages of CDP coating systems include poor self-smoothing, increasing leached layers over time, a variable biocide release and a short coating lifetime (Table 1; Yebra et al. 2004). It may be possible to extend the effective lifetime of CDPs by regular in-water cleaning that removes the leached layer and rejuvenates the paint film (Finnie & Williams 2009).

In the US, the majority of navy ships are coated with rosin-based copper CDPs. These ships spend long periods of time inactive in a port. Long periods of inactivity require in-water cleaning which maintains the ships within specified operational conditions. Proactive cleaning activities should not significantly affect coating depletion over time to achieve the desired dry-dock cycles of 12 years for these navy ships (Tribou & Swain 2017), but if vessels would be cleaned reactively, coatings could be expected to deplete substantially, reducing the dry-dock cycle (Davidson et al. 2016).

CDP paints are based on the physical process of hydration and dissolution of the soluble binder. This is the key difference between CDP paints and SPC paints where the ablative mechanism is based on hydrolysis.

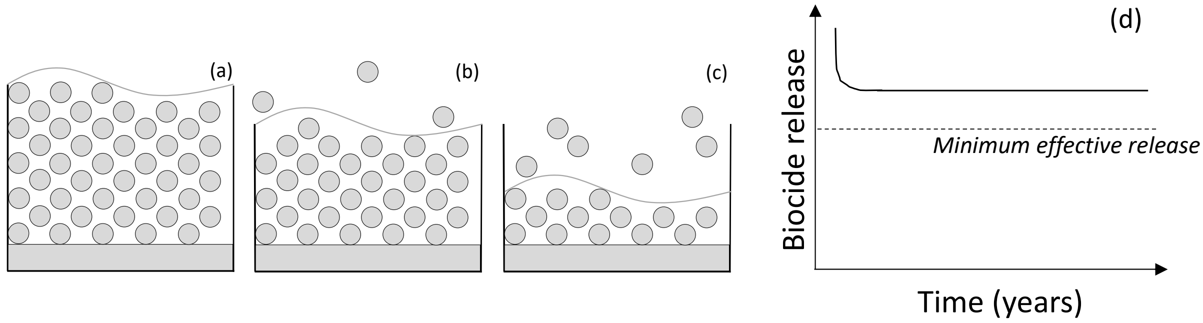
Difference between hydration and hydrolysis

Hydration: the process of surrounding dissolved ions by water molecules

Hydrolysis: the splitting of a molecule by the addition of water

Source: Timberlake (2019)

Self-polishing copolymer (SPC) anti-fouling paints constitute a significant improvement over conventional coatings and their exponential decline of biocide release rates over time (Table 1). SPC paints consist of copolymers, made up of biocides chemically bonded to polymer backbones of the paint binder (Figure 6a, light grey circles). These paints release copolymers that are hydrolysed (split up) by contact with and motion through seawater, releasing the biocides (Figure 6b). This reaction takes place within a few nanometres of the coating surface which keeps leached layers thin during periods of immersion (Floerl et al. 2010). As each molecular layer of the copolymer reacts and dissolves through slow and controlled hydrolysis, the layer below can react, resulting in continuous surface renewal which is called 'self-polishing'. The quantities of insoluble binder in the paint are small. Consequently, the leached layer of SPC paints remains thin, allowing the biocide release rate to be virtually constant for the lifetime of the paint (Figures 6c,d; Almeida et al. 2007; Finnie & Williams 2010). SPC paints vary in their self-polishing rate (µm per year) to cater for vessels with different operating speeds and activity patterns. The polishing rate and biocide release increase with increased seawater temperature and vessel speed (Kiil et al. 2001, 2002; Yebra et al. 2004).



Modified from Anisimov et al. (2019) and Bressy et al. (2009)

Figure 6: Self-polishing copolymer anti-fouling coatings.
Light grey circles represent biocide particles. The layer of biocide becomes thinner over time through self-polishing (Figures 6c,d) and because there is no build-up of the leached layer, it remains thin.

SPC paints have been used widely in the shipping industry because of their constant rate of biocide release and other advantages. Close to 70% of all commercial shipping was using these paints in 1999 (Almeida et al. 2007). Earlier versions of SPC paints used TBT as a copolymer. However, TBT has well documented harmful side effects on non-target marine organisms and the marine environment including bioaccumulation and biomagnification (Hellio & Yebra 2009; Townsin & Anderson 2009; Dafforn et al. 2011; Zhao & Wang 2015) and was therefore banned through an international convention, as of September 2008 (IMO 2001). Due to this regulatory change, paint companies have invested in research into development of anti-fouling coatings that contain less toxic biocides (Webster & Chisholm 2009). New technology SPC paints may have effective service lives of up to 60 months or beyond, similar to TBT-SPC paints (Candries et al. 2003; Omae 2003;

Floerl et al. 2010; Pei & Ye 2015; Pradhan et al. 2019; Hempel 2020; Lewis 2020), but a number of authors believe that TBT-free SPC paints do not actually achieve the same effective service lives (Almeida et al. 2007; Bressy et al. 2009; Lejars et al. 2012).

Hybrid ablative self-polishing systems combine the properties of CDPs and SPC paints (Bressy et al. 2009), bringing together the hydrolysable SPC technology with the rosin-based CDP technology (Fox & Finnie 2003). In hybrid systems, the release of biocides is based on hydrolysis and hydration, which means that they exhibit both CDP features (surface tolerance, attractive volume solids) and SPC features (self-polishing, controlled release of biocides and reduced thickness of leached layer)(Lejars et al. 2012). In general, hybrid paints remain effective in preventing biofouling between 3 and 5 years (Table 1). Rosin compounds are key ingredients in hybrid formulations (Hellio & Yebra 2009) and are combined with TBT-free SPCs or other polymers at larger amounts than in acrylate SPC paints (Finnie & Williams 2009).

In *metallic coating systems* copper or copper-nickel alloy is mixed into the coating system as either metal sheathing or metal particles. These coating systems are not practical for use on vessels because coating renewal is not possible. Their main use is for offshore and fixed installations (Georgiades et al. 2018).

Enzyme-based coatings are alternatives to metal-based anti-fouling agents. Enzymes are inexpensive and assumed to be environmentally friendly because they biodegrade rapidly (Cordeiro & Werner 2011). The fouling inhibition properties of these coatings can be based on direct or indirect effects (Olsen et al. 2007). Direct enzymatic anti-fouling refers to enzymes that actively interfere with anti-fouling organisms. Direct enzymatic anti-fouling can be 'biocidal', when the substrate of the enzyme is vital for the fouling organisms. Or it can be 'adhesive degrading', when the substrate of the enzyme affects the ability of the fouling organism to adhere to the surface. Indirect enzymatic fouling is based on enzymatic generation of biocides from substrates present in seawater or in the coating (Olsen et al. 2007; Lejars et al. 2012).

Enzymes used for direct 'biocidal' enzymatic anti-fouling are within the scope of the Biocidal Product Directive of the European Union and must be approved before use (Olsen et al. 2007). Only one enzyme additive for water- or solvent-based paints was commercially available in 2012, for the yachting market (Lejars et al. 2012). Before this technology can be used more widely research needs to remove obstacles to their usability such as insufficient enzyme stability and activation, broad spectrum efficiency and amount of biocide generated (Olsen et al. 2007). Lejars et al. (2012) noted that long-term efficiency of enzyme-based coatings toward all fouling organisms remains to be reported.

As an example for surface engineering using biocides with non-toxic by-products, a study using zinc oxide nanorods (tiny hexagonal structures) demonstrated that nanorod coated glass surfaces significantly reduced the density and viability of bacteria. The nanorods attained their anti-fouling properties through the formation of reactive oxygen species which damaged microbial cell walls (Sathe et al. 2016). These coatings are also called photocatalytic coatings because of their ability to catalyse the production of reactive oxygen species such as hydrogen peroxide (Morris & Walsh 1999; Ciriminna et al. 2015). Hydrogen peroxide is not environmentally toxic following its complete degradation (Linley et al. 2012).

6.1.1.2 Non-biocidal and non-toxic anti-fouling solutions

Concerns about the adverse impacts of biocides on the environment have fuelled research into non-biocidal solutions (Yebra et al. 2004; Webster & Chisholm 2009), with foul-release coatings (FRCs) considered the most practical (Townsin & Anderson 2009). Nevertheless, biocidal anti-fouling solutions still dominate the anti-fouling market for commercial and recreational vessels and will do so for the foreseeable future, as market data shows, with improved products. In 2014, the market share of FRCs was only around 10%, but all major suppliers of anti-fouling coating products now include elastomeric FRCs in their product range (Ciriminna et al. 2015). FRCs are evolving more quickly than the established biocidal anti-fouling business model (Rittschof 2009) and Lindholdt et al. (2015) expected FRCs to continuously gain shares of the industrial marine coating market considering their existing potential for drag reduction and biofouling control. In 2021, SPCs are still holding a larger proportion of the marine coatings market compared to FRCs (Han et al. 2021), but the potential for increased regulation of antifouling biocides (NZ EPA 2013; ECHA 2021) may provide incentives for that relationship to change.

Foul-release coatings are non-biocidal and have surface properties that minimise adhesion of biofouling organisms and facilitate their removal by water flow (Finnie & Williams 2009; Hellio & Yebra 2009). The surface of FRCs is smooth and has a low friction coefficient due to low surface energy. Surface energy is one characteristic of the substratum that influences the colonisation process, whereby lower surface energy reduces the adhesion strength of fouling organisms (Callow & Fletcher 1994). A low surface energy facilitates water flow along the surface and the removal of weakly attached fouling organisms (Anisimov et al. 2019). Fluoropolymers and silicone elastomers are the most used compounds in FRCs to achieve these desired surface properties but they differ in their foul release mechanism (see Yebra et al. 2004). Silicone-based coatings are deemed more effective in preventing biofouling because they can be applied in thicker layers, allowing a more efficient peeling action of the silicone away from the marine adhesive (Yebra et al. 2004; Lewis 2009; Floerl et al. 2010). The effectiveness of silicone-based FRCs can be further enhanced through addition of silicone or fluorinated oils (Lewis 2009; Galhenage et al. 2016).

FRC technology is expensive due to the higher initial cost of paint and application (Lejars et al. 2012) and is not suitable for all vessel types (Callow & Callow 2009; Townsin & Anderson 2009). Biofouling organisms are capable of attaching to the coatings, but most fouling types are removed at voyage speeds greater than 15 knots. Barnacles may detach at speeds around 10 knots but biofilm can remain intact even at speeds above 30 knots (Candries et al. 2001). The application of FRCs is therefore limited to high speed (>15 knots)/high activity vessels (Callow & Callow 2009), such as fast ferries, container ships, gas carriers, vehicle carriers, tankers, reefers (refrigerated cargo ships), cruise liners and large roll-on, roll-off (RoRo) vessels (Townsin & Anderson 2009; PPG Industries 2020). However, producers of some commercially available FRCs claim that they can be used on all vessel types (PPG Industries 2020; AkzoNobel 2020a) with speeds >10 knots (AkzoNobel 2020a), according to coating specifications (Townsin & Anderson 2009; Lejars et al. 2012). The efficacy of FRCs can last for 5 – 10 years if properly maintained (Floerl et al. 2010; Lejars et al. 2012; Anisimov et al. 2019), or even longer (Townsin & Anderson 2009). However, one review reports a lifetime of only 2 – 5 years for FRC systems (Chambers et al. 2006).

Current silicone-based FRCs are susceptible to scraping or gouging damage caused by anchor chains or when moored alongside. As these coatings rely on the special properties of their surface to minimise adhesion of fouling organism, any damage would have a considerable impact on their efficacy (Townsin & Anderson 2009; Lejars et al. 2012). Also, if vessels stay inactive for an extended period or do not maintain operating speeds to remove fouling organisms FRCs are likely to be less effective and hull cleaning is required (Holm et al. 2003; Scianni et al. 2019). However, reactive in-water cleaning or proactive grooming do not release biocides into the surrounding environment. When compared with biocidal anti-fouling coatings in a field experiment, foul release coated surfaces accumulated more biofouling organisms following a stationary period of 28 days, but that difference levelled out after 45 days (Scianni et al. 2019). Despite their reputation as an environmentally friendly alternative to biocidal anti-fouling coatings, FRCs may not be as harmless as widely thought. Rittschof (2009) argues that most FRCs contain toxic additives and release compounds such as silicones into their surroundings with unknown consequences for the environment. Corroborating this assessment, Nendza (2007) concluded that inert silicone oils, used as additives in FRCs, have the potential to physical-mechanical trap and suffocate marine organisms.

Innovative research is experimenting with improving the adhesion and durability of the silicone-based coating material while retaining the foul release properties of the silicone component, thereby developing *hybrid silicone-based FRCs* (Table 2). For example, researchers incorporated nanofillers, or modified the silicone matrix with components such as polyurethane, epoxy resins, sol-gels, hydrogels, fluorinated segments or introduced biocides (Lejars et al. 2012). Hybrid biocidal/FRCs combine the characteristics of biocidal coatings with the characteristics of FRCs (see Lejars et al. 2012; Verma et al. 2019; Wanka et al. 2020). These biocidal FRCs are resistant to fouling during idle periods (up to 120 days) and protect vessels operating with long service intervals (up to 90 months) which was the main limitation of first generation FRCs (Ciriminna et al. 2015). A further approach involves the use of zwitterionic polymers. Novel coatings incorporating these polymers displayed non-fouling properties and had low fouling adhesion similar to or better than commercial control coatings and standards (Webster 2010; Han et al. 2021).

Like other marine paints, the use of silicone-based coatings in the shipping industry paints a picture of varied success depending on the developmental stage of the used product at the time. In 2003, the international vessel operator Maersk started application of biocide-free silicone paint on container, tanker and supply vessels. However, only four years later the shipping company stopped applying silicone-based paint due to slime layer development and a fast decrease in efficiency of vessels with that paint. Maersk concluded that the increase in fuel consumption through FRCs had a higher environmental impact than the use of biocidal coatings (Maersk 2007). In contrast, the application of third generation hydrogel silicone foul release technology on a large carrier vessel showed that silicone hydrogel coatings effectively protected the ship's hulls from slime and algae for up to 25 months with an estimated activity of 60% of the time and average cruising speed of 13 knots. This demonstrated that this technology is effective at low vessel speed and low activity (Thorlaksen et al. 2010).

A study of a range of different vessel types encompassing a wide range of operational profiles showed that on hull surfaces, SPC coatings and FRCs offered longer and more reliable protection from biofouling than CDP coatings (Lewis 2016). The application of FRCs to intake grates and propeller blades can minimise biofouling attachment, survival and growth (Lewis 2016). However, these conclusions are restricted to generalisations, because of the lack of data which did not allow statistical analysis.

Table 2: Other potential non-biocidal or non-toxic anti-fouling solutions

Type	Description	References
Hybrid silicone-based FRCs	The silicone matrix of FRCs is modified by adding other materials to improve desired properties	Lejars et al. 2012 Verma et al. 2019 Wanka et al. 2020
Engineered surface texture, nanotechnology	This approach involves modifying physical properties of a material on micrometre scale to create nontoxic anti-fouling surfaces or coatings	Callow & Callow 2009 Scardino 2009 Carve et al. 2019 Ware et al. 2018
Marine natural products*	Secondary metabolites produced by marine organisms can act as anti-foulants that could be incorporated into existing coating technology	Rittschof 2009 Pereira & Costa-Lotufo 2012 Qian et al. 2015 Wang et al. 2017
Pharmaceutical products*	Existing pharmaceuticals offer a source of new anti-fouling agents that could be incorporated into existing coating technology	Rittschof 2009 Rittschof et al. 2010 Qian et al. 2015
Fouling resistant surfaces	The aim of these chemically engineered surfaces is to prevent biofouling by designing specific surface properties (hydrophobicity or hydrophilicity)	Genzer & Efimenko 2006 Marmur 2007 Bixler & Bhushan 2012 Han et al. 2021
Enzyme based coatings	Enzymes can be integrated into coating technology to target and degrade the compounds that attach fouling organisms to a surface	Olsen et al. 2007 Cordeiro & Werner 2011 Aykin et al. 2019
Peptides	Peptides are short chains of amino acids. Researchers aim to develop peptide coated materials that have anti-fouling properties	Cahill et al. 2019a Arul et al. 2020
Biotechnology	The development of artificial molecules, such as Selektope® with repellent effects on fouling organisms	i-tech 2021
Ultra-hard coatings	Coatings that are non-toxic, inert and long-lasting. This coating technology requires regular in-water cleaning of vessels, using special equipment and tools.	Subsea Industries 2021

*These products should be non-toxic to be selected as candidate antifoulants (Wang et al. 2017), but they are not 'non-biocidal', because they do have an impact on marine organisms. Per definition, a 'biocide is a substance that destroys or inhibits the growth or activity of living organisms' (Merriam-Webster online dictionary 2021).

Molino et al. (2009) compared the performance of three different coating types using experimental panels submerged in seawater. They used two SPC anti-fouling coatings, one containing TBT and the other TBT free, and an FRC. Results showed that the FRC suffered the quickest colonisation by bacteria which reached area coverage of 40-50% within 2-4 days compared to 3-8 days for the biocidal anti-fouling coatings. After 16 days all three coatings were significantly fouled.

Another strategy for developing non-toxic anti-fouling solutions is to *engineer a surface topography* that makes it harder for fouling organisms to attach or weakens their attachment strength. A recent review found that complex and hierarchical surface designs were more effective against biofouling than regular geometric features. However, the effectiveness of this strategy against fouling is unclear as most studies investigated mechanisms and performance of engineered surfaces in the laboratory using a limited range of test species (Carve et al. 2019). Ware et al. (2018), for example, designed a nanostructured wrinkled surface mimicking the lubricating mechanism of the pitcher plant. The nanostructured wrinkled surface, infused with silicone oil, inhibited bacterial fouling and reduced algae attachment in a field study, showing potential for translation into a commercial application.

Biomimetics refers to studies that copy aspects of biology to develop similar products for a specific purpose. Biomimetics research into fouling prevention includes investigation and development of natural products, pharmaceuticals (medicinal drugs), and surface structures (Rittschof 2009; Ware et al. 2018; Clasen & Kesel 2019). Source material for this type of research are not restricted to the marine environment, for example, terrestrial plant surfaces or seeds can be used as models for non-toxic anti-fouling solutions (Ware et al. 2018; Clasen & Kesel 2019). Clasen & Kesel (2019) investigated why some seeds of tropical and subtropical land plants can remain free of fouling when drifting in marine waters. The shape and size of drifting plant seeds were found to be important factors in minimising fouling, but surface microstructures most likely had the greatest influence, for example regular honeycomb surfaces. This study excluded the influence of chemical substances.

Scientists have actively investigated the use of *natural products for fouling protection* for decades (Lewis 2009; Rittschof 2009), studying organisms that are free of fouling on their surfaces due to inherent natural chemical defence mechanisms (Qian et al. 2015; Wang et al. 2017). Plants and animals produce and secrete secondary metabolites, compounds not needed for growth and development, as a defence to predators and also to prevent settlement (Kutchan et al. 2015). But the effectiveness of anti-microfouling defence of natural products may vary seasonally (e.g., Saha & Wahl 2013). About 700 marine natural products or secondary metabolites have been reported to exhibit anti-fouling properties. However, only a few of those can be considered potential candidates for commercial products because of fundamental flaws and issues with developing natural products as anti-foulants, including (i) inhibitory effects of natural products only affect a narrow range of species, (ii) toxicological and ecotoxicological information on compounds is limited, (iii) anti-fouling properties of most compounds were tested in laboratory assays but not verified in the field, and (iv) the need for large scale synthesis of compounds and compatibility with base paint ingredients (Yebra et al. 2004; Qian et al. 2015). These issues also relate to human made products. Similarly, large numbers of *pharmaceuticals* are available but need to be evaluated for their potential to act as anti-fouling agents within existing coating technology (Qian et al. 2015). Pharmaceuticals have known chemical properties, biological potency and synthesis procedures which facilitates government registration and commercialisation when compared to natural products (Rittschof 2009; Rittschof et al. 2010). As pharmaceuticals are stable by design they may build up in the environment, requiring research into their de-engineering or degradation (Lewis 2009).

Scientists have been studying the functionality of natural surfaces in flora and fauna for inspiration in their quest to develop *surfaces that are resistant to biofouling* without the use of toxic substances (Bixler & Bhushan 2012; Han et al. 2021). Several natural models have been studied, including whale and shark skins, echinoderms, crustaceans, red macroalgae, insects, ferns and bivalve molluscs (Scardino 2009, Bixler & Bhushan 2012). Chemical engineers, for example, are investigating how to prevent biofouling on submersed surfaces in water by observing how surface properties affect wettability of materials in nature. The lotus leaf is one example of a popular study object due to its remarkable self-cleaning mechanism. To design surfaces that are resistant to biofouling, engineers are exploring options that tailor their chemical and physical properties (Genzer & Efimenko 2006). One option is about designing a surface that prefers contact with water over that with biological matter, thus repelling fouling organisms by mirror imaging the lotus effect. Such surfaces would be super-hydrophilic. The other option involves developing surfaces that are super-hydrophobic (water repellent) underwater, by making them rough so they can support an air film between them and the surrounding water (Marmur 2007).

Commercial enzymes can affect the ability of fouling organisms such as bacteria to adhere to submerged surfaces by targeting the compounds produced by fouling organisms to anchor cells to the surface (Cordeiro & Werner 2011). Some enzymes could be incorporated into or onto an anti-fouling coating to inhibit adhesion (Leroy et al. 2008; Aykin et al. 2019). However, the successful incorporation of enzymes into marine anti-fouling coatings, and achieving broad spectre anti-fouling with long-term efficacy, remains a challenge (Cordeiro & Werner 2011) due to issues with enzyme stability and activity (Aykin et al. 2019).

Biofouling is a problem in medical settings because it can damage the functioning of medical devices. This issue has sparked medical research into the use of peptides as components of anti-fouling coatings that can prevent biofouling without releasing harmful chemicals. Peptides are non-toxic because they degrade into benign amino acids when they are in the environment (Arul et al. 2020). This method can also find application in other settings, such as marine biofouling. The Cawthron Institute in New Zealand, for example, is currently synthesising and assessing potential candidate peptides for use in anti-fouling formulations (Cahill et al. 2019a).

Biotechnology can also offer solutions, such as the prevention of attachment of specific fouling organisms. Selektope®, for example, is an organic molecule that was developed for use in marine paint systems to bio-repel barnacles. When barnacle larvae come into contact with this molecule, they become hyperactive (they are put into 'swimming mode') and cannot attach to the surface painted with Selektope®. The effect is reversible and larvae can return to their normal state (i-tech 2021).

Other non-toxic alternatives to biocidal anti-fouling coatings include 'smart' polymers, fibre coatings, scrubbable and inert coatings (e.g. used in the Baltic, BMEPC 2020), electromagnetic and sonic deterrents, and non-leaching biocidal coatings. These technologies can inhibit attachment and/or growth of biofouling organisms but not all of them have proven to be practical solutions for wide application because they either (i) have not been developed into a functional coating system, (ii) are expensive to apply, (iii) are not durable, (iv) cannot offer long-term protection from a broad spectrum of fouling organisms, or (v) cannot easily be applied under varying shipyard conditions (Lewis 2009; Floerl et al. 2010). Ultra-hard, inert coatings such as Ecospeed, for example, have been developed into a functional coating system and are used by ice-going vessels, cruise ships and yachts. But these coatings need to be cleaned regularly using specially developed equipment and tools to keep fouling at microfouling level (Subsea Industries 2021). Scardino (2009) concluded that multiple strategies, including nanotechnology, natural products and surface chemistry, will be required to achieve broad-spectrum fouling resistance.

6.1.1.3 Presence/absence of anti-fouling coatings

The utilisation of appropriate anti-fouling coatings on vessel hulls is currently the best defence against the accumulation and translocation of exotic marine species while the vessel is in service. To be effective, the choice of anti-fouling coating needs to fit the operational profile of a vessel. Vessel operators need to consider the different needs of vessels areas (main hull and niche areas) and choose potentially multiple anti-fouling systems to achieve overall biofouling minimisation (Georgiades et al. 2018). Any vessel that does not possess an anti-fouling coating or foul release coating will accumulate greater levels of biofouling and pose a greater likelihood of translocating exotic marine species than vessels with effective anti-fouling systems applied.

The extent of marine biofouling depends on several abiotic and biotic factors, including salinity, temperature, nutrient levels, flow rates and the intensity of solar radiation. Fouling pressure varies with geographical location and the risk of fouling in temperate, cold and polar regions is generally lower compared to intense fouling pressures reported in sub-tropical and tropical regions (Visscher 1928; Hellio & Yebra 2009). Coatings applied to vessels operating in regions with ice and sub-zero temperatures are adapted to these conditions. Some vessels that only operate in cold waters (e.g., the Baltic Sea) may not have anti-fouling coatings applied (but see Table 2 – ultra-hard coatings) as some vessel operators assume that fouling organisms do not cause issues in those environments (Maersk 2007). Currently, this may be the case as only very low numbers of exotic marine species have been recorded around Antarctica and sub-Antarctic Islands, with no established populations (McCarthy et al. 2019). However, ongoing climate change will alter conditions for exotic marine species and will, together with predicted increases in human activity in these regions, increase the risk of exotic marine species establishment (McCarthy et al. 2019; Avila et al. 2020).

There are certain areas on any type of vessel that are often not covered by any anti-fouling coating or to the extent possible, such as cathodic protection anodes, propellers and propeller shafts (propeller shaft casings are coated), rudder stocks and docking block support strips (Coutts & Taylor 2004; Lewis & Coutts 2009). This makes these niche areas, and areas with insufficiently applied or poor condition anti-fouling coating, hotspots for biofouling and areas of biosecurity concern (Dobroski et al. 2015; Davidson et al. 2016). However, propeller blades that are not covered by an anti-fouling coating are less of a biosecurity concern on active vessels because the movement of the blades through water inhibits attachment of most macrofouling organisms. Nevertheless, some hydrodynamic-insensitive taxa with a high percentage cover may be able to persist (Coutts & Taylor 2004).

6.1.1.4 Age and condition of anti-fouling coatings

Dry-dockings, undertaken for various reasons, such as vessel cleaning, application of anti-fouling or foul release coatings, and classification society inspections are significant costs to vessel operators and interrupt vessels' active service periods. The marine coating industry invests heavily in research to improve the effectiveness and service life of anti-fouling coatings (Edyvean 2009; Davidson et al. 2016) to reduce dry-docking intervals driven by vessel management. The effectiveness of anti-fouling coatings depends on a range of factors, including its age, condition (depends on compatibility with vessel operational profile, the environment, etc), biocide concentration and release rate, the dry film thickness and the quality of application (Georgiades et al. 2018).

The age of anti-fouling coatings (i.e. calculated from the time of its application) is a useful indicator for determining the biofouling risk of a vessel as generally the older the coating the greater the likelihood that the vessel's hull will possess biofouling organisms, potentially including exotic marine species (Floerl & Inglis 2000, 2005; Floerl et al. 2005a; Ashton et al. 2006; Davidson et al. 2010; Sylvester et al. 2011; Davidson et al. 2012; Lacoursière-Roussel et al. 2012; Clarke Murray et al. 2013; Barry et al. 2015; Simard et al. 2017). While the effectiveness of anti-fouling coatings is dependent on many factors (e.g., type of coating, biocides used, environmental conditions, and vessel activity), the leaching rate of toxic biocides of insoluble matrix and CDP anti-fouling coatings declines with age to a point where they pass a threshold value and are unable to further deter biofouling settlement (e.g. Almeida et al. 2007; Anisimov et al. 2019). However, SPCs have a nearly constant biocide release for the lifetime of the paint, which is determined by coating thickness and ongoing maintenance (Almeida et al. 2007). Older anti-fouling and foul release coatings are also likely to have suffered more damage over time through wear and tear (such as grounding, collision or mechanical impact), which will increase the likelihood of successful biofouling colonisation in the localised area of the hull where paint has been removed as a result of impact.

However, a few studies did not find a significant relationship between the age of anti-fouling coatings and the abundance of fouling. For example, Clarke Murray et al. (2011) found that fouling of niche areas on surveyed recreational boats was not related to anti-fouling coating age but concluded that this may have been due to inadequate application of anti-fouling coatings on difficult to access niche areas. Other studies attributed the lack of a positive relationship to poor quality of hull husbandry (Ashton et al. 2014), substantial variation among vessels with coatings <30 months old (Davidson et al. 2010) and a small sample size or the influence of multiple factors (Inglis et al. 2010; Zabin et al. 2014).

The way that anti-fouling coating is applied is also important. Poor or improper application or surface preparation can reduce the effective lifespan of the coating. The producers of anti-fouling coatings provide instructions about how coatings should be applied, specifying the required surface preparation, coating thickness, presence of a primer coating, the method of application, application conditions and the minimum drying time before flooding (ABS 2017). Underwater hull coating system application is best performed by professional paint applicators, and the surface preparation and application overseen and approved by an inspector from the paint company (Batra 2014). This is the normal procedure for medium to large vessels in commercial dry-docks or shipyards, but not always the case for smaller vessels painted on slipways or in boatyards (TCS 2004; ABS 2017).

Piola and Johnston (2008) demonstrated that even small areas of hull that escaped treatment with anti-fouling coatings and treated areas that received scrapes can provide sufficient conditions for the formation of fouling assemblages. Signs of poor coating condition include peeling, chipping and visible paint wear to base layers (Hopkins & Forrest 2010).

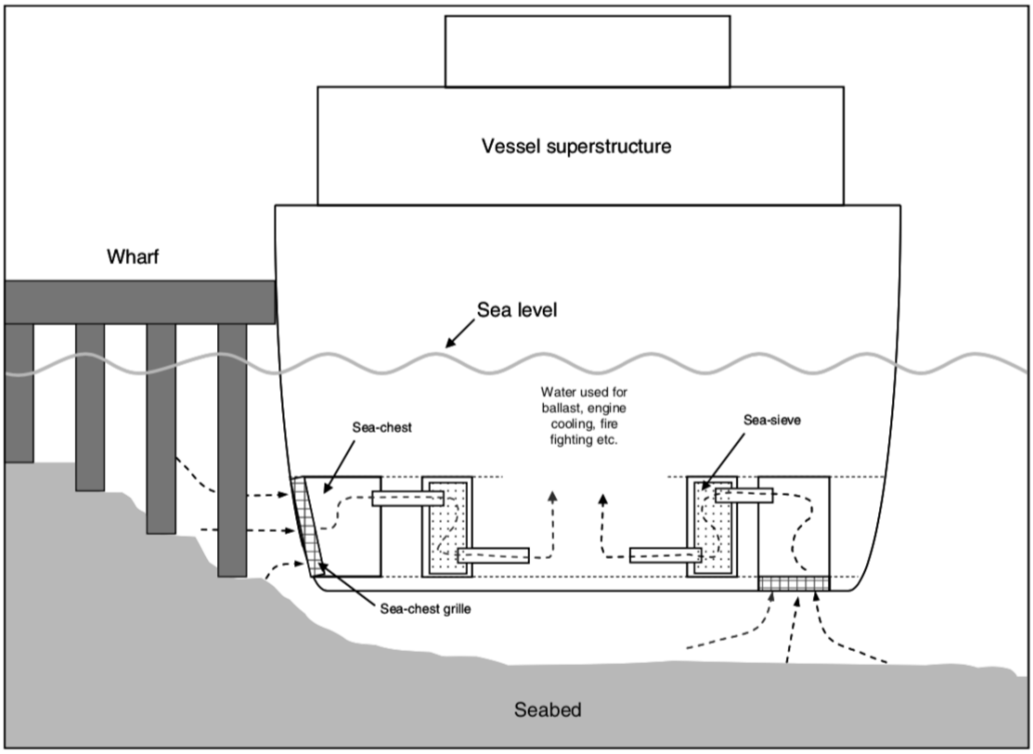
Owners of commercial vessels increasingly apply different coatings to different vessel surfaces (hull vs certain niches) based on their predicted performance in areas subjected to laminar flow and those that are not (Ian Davidson, pers. communication). SPC coatings with the appropriate specifications (dry film thickness, biocide content, polishing rate, etc.) are suitable for all vessels (Hempel 2020; Jotun 2020a), but cost is a key factor influencing selection of coating type. Vessels with low to medium speed, low activity and an uncertain operational profile including long lay-up periods (e.g. navy vessels, workboats) require a faster polishing, high thickness anti-fouling coating. Vessels with medium to high speed, high activity and a predictable operational profile (e.g. commercial vessels – cargo, cruise) require slower polishing and lower thickness anti-fouling coatings (Yebra et al. 2004; Bressy et al. 2009; MPI 2018b; Anisimov et al. 2019). Both CDP and SPC coatings can be formulated as hard or soft coatings (URS 2007). Faster polishing, soft biocidal CDP and SPC coating systems are recommended for the treatment of sea chests (Lewis 2016; Georgiades et al. 2018).

6.1.2 Marine Growth Prevention Systems

Marine growth prevention systems (MGPS) are technologies designed to prevent fouling in the sea chests and internal seawater systems of a vessel. The internal piping network of internal seawater systems is used to supply water for fire suppression, ballast, cooling and heat exchange and is prone to heavy biofouling because it is inaccessible for preventative paint application and ongoing reactive maintenance (Coutts & Dodgshun 2007; Grandison et al. 2011). Heavy levels of biofouling can affect the operability of a vessel and when essential parts of the internal piping are blocked, it can also reduce the effective uptake of water to onboard systems and change intake flow regimes. This may degrade the structural integrity of the internal pipework and fittings and lead to corrosion of essential structures (Grandison et al. 2011).

Sea chests are recesses built into a vessel's hull, sitting below the waterline (Figure 7). They house the seawater intake pipes for internal seawater systems and are considered to be a potential mechanism for transport and dispersal of exotic marine species (Coutts et al. 2003). Extremes in water-flow can reduce the effectiveness of anti-fouling coatings applied to sea chests when compared to the uniform areas of the hull (Coutts & Dodgshun 2007; section 6.2.1).

Sea chests and internal seawater systems can be fitted with a MGPS to prevent biofouling growth in the pipework and to maintain essential free flowing seawater. Although the efficacy of MGPS at mitigating biofouling varies considerably, vessels that possess operational MGPS tend to have lower levels of biofouling (Coutts & Dodgshun 2007). A combination of systems based on a vessel's operational profile may be the best approach as it is unlikely that a single system is able to control all fouling pressures (Grandison et al. 2011). Where MGPSs fail to prevent biofouling, as has been reported (Lewis et al. 1988; Grandison et al. 2011; Frey et al. 2014; Lewis 2016), reactive treatments are required to manage biofouling.



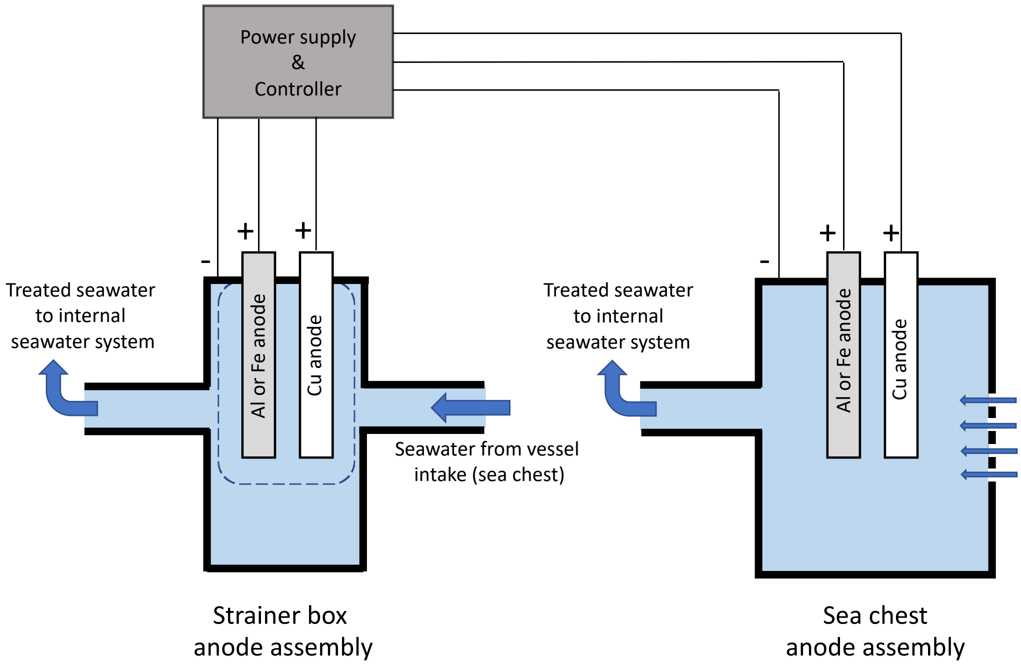
Source: Coutts & Dodgshun 2007

Figure 7: Schematic diagram of a vessel's sea chest system

The three main types of MGPS are sacrificial anodic copper dosing, electrochlorination and direct chemical dosing (Lewis 2016).

6.1.2.1 Sacrificial anodic copper dosing

To prevent biofouling, sacrificial anodic copper dosing systems usually consist of a paired copper anode for anti-fouling and an aluminium or iron anode for corrosion control that are placed into the internal seawater system, either close to the intake point in the sea chest or in the strainer box which is a component containing a reusable filter (Figure 8; Grandison et al. 2011). The anodes are linked to a power supply that directs an electrical current to the anodes. The electrical current releases copper and aluminium (or iron) ions at a rate to achieve the desired concentration which is dispersed by the waterflow throughout the piping network. The metal ions produce an anti-fouling and anti-corrosive layer on the internal pipe surface (Grandison et al. 2011; Eyres & Bruce 2012). Fouling organisms that cannot adhere to the surface of sea chests, strainers, piping or box cooler tubes, pass through the cooling water system and are discharged (Cathwell 2019).



Modified from Grandison et al. (2011)

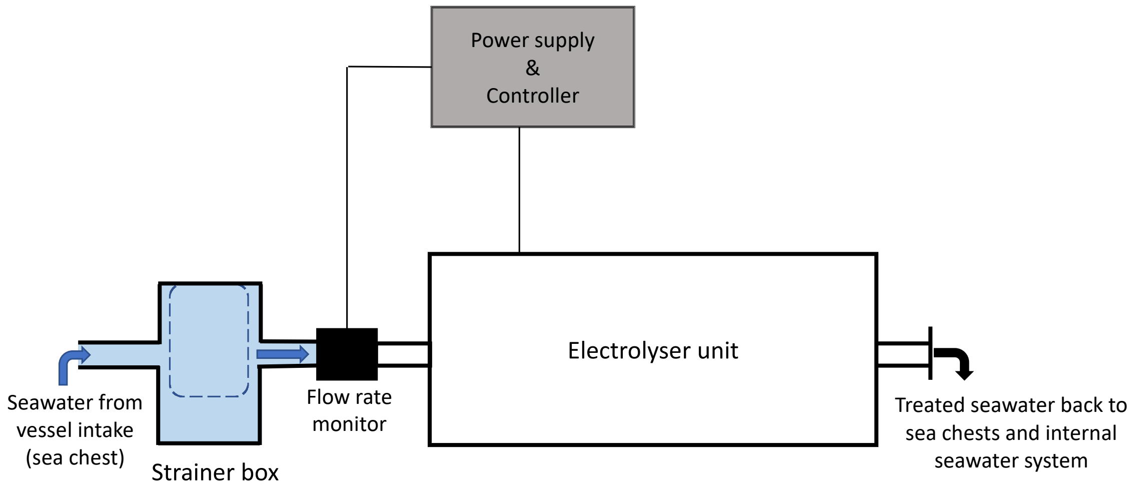
Figure 8: Sacrificial anodic copper dosing MGPS

Sacrificial anodic copper dosing is an established technology and relatively inexpensive compared to some remediation strategies for internal seawater systems (Grandison et al. 2011). Depending on the conditions a vessel operates under, the dosage of dissolved copper may need to be increased to effectively prevent biofouling, leading to greater running costs as the sacrificial copper anodes dissolve more quickly than specified. Another problem for the use of sacrificial anodic copper dosing systems is the existence of copper tolerant fouling species (Weiss 1947; Russell & Morris 1970; Piola & Johnston 2006; McElroy et al. 2017). These species can grow despite high concentrations of copper in their environment. Copper is considered a heavy metal pollutant and its discharge is regulated and even banned in some jurisdictions (Grandison et al. 2011).

Lewis (2016) expressed doubts about the effectiveness of copper anodic systems. Biofouling was present in most surveyed sea chests that had copper anodes installed even when systems were operated to the recommended settings and anodes replaced when depleted. He concluded that the target dose of 2 ppb copper in the flow, the recommended industry standard, is insufficient to prevent biofouling attachment and growth. Regardless of the target dose it would be a challenge to achieve uniform copper concentrations, even from multiple anodes in a sea chest (Lewis 2016).

6.1.2.2 Electrochlorination

Chlorine is the most commonly used biocide to prevent or treat biofouling within aquatic systems (Growcott et al. 2016). Electrochlorination is the conversion of chlorine in seawater into sodium hypochlorite using a low voltage DC current. Hypochlorite generators direct seawater from the vessel intake to an electrolyser cell (electrochlorinator), where the conversion takes place via the principle of electrolysis. The chlorinated water is then injected into the sea chest and internal seawater system for dispersal (Figure 9, recommended chlorine concentrations 0.2-0.5 ppm, Grandison et al. 2011). Sodium hypochlorite is an effective anti-fouling agent in itself, but it also reacts readily with the concentrations of bromide in seawater to form bromine residuals such as hypobromous acid (Taylor 2006). The effects of seawater chlorination are therefore boosted by bromine residuals which are effective oxidisers and disinfecting agents.



Modified from Grandison et al. (2011)

Figure 9: Electrochlorination MGPS unit

Electrochlorination on ships is an established and relatively inexpensive technology because the disinfectant (sodium hypochlorite) is generated from seawater. Chlorination may induce corrosion of the internal copper-nickel pipes (Grandison et al. 2011), but there is only limited information on that effect. As a precaution, overdosing with sodium hypochlorite should be avoided (Schleich 2004; Grandison et al. 2011). Electrochlorination systems can easily be scaled up, but they also require having chemicals on board to neutralise hypochlorite before discharge (Stehouwer et al. 2015).

6.1.2.3 Chemical dosing systems

Chemical dosing systems are fitted on board of vessels and automate injection of liquid anti-fouling chemicals into the intake water from an internal reservoir which is then further distributed into the internal piping system to inhibit biofouling settlement and growth. Lewis (2016) observed that chemical dosing systems were ineffective in preventing macrofouling on two surveyed vessels because mussels and barnacles were growing in pipes downstream of the feed.

Copper-nickel alloys are not a MGPS but they are a material that is frequently used for internal pipework because they are resistant to seawater corrosion and biofouling (Powell & Michels 2000; Schleich 2004; Ma et al. 2015). Copper-nickel piping exert some passive fouling control when a protective corrosion product film containing cuprous oxide forms at the surface of the piping, but this level of protection is considered inadequate under heavy fouling pressure (Grandison et al. 2011).

6.2 Vessel characteristics and operating profile

In addition to technology to prevent the attachment of fouling organisms to vessels, vessel design, vessel speed, stationary periods and transit routes also influence the level and type of biofouling present (Table 3).

Table 3: The influence of vessel characteristics and operating profile on biofouling

Factor	Effect	References
Vessel design Vessels comprise the hull, some moving parts such as the propeller and rudder, and a number of niche areas. Vessel design determines the number, size and complexity of niche areas.	High levels of biofouling can be present in areas that are: • protected from hydrodynamic forces; • not painted with anti-fouling coatings; • hard to access and clean; and • exposed to high turbulence and cavitation. Niche areas are considered hotspots of biofouling accumulation, especially sea chest gratings; sea chests and internal pipework; DDSS; and thruster tunnel gratings. Ship type affects the size of wetted surface area, which is an important factor for biofouling risk because of the scale of submerged surface area. The more surface area is available, the more fouling organisms can attach.	Lewis 2002 Coutts & Taylor 2004 Coutts & Dodgshun 2007 Davidson et al. 2009 Lewis & Coutts 2009 Inglis et al. 2010 Piola & Conwell 2010 Clarke Murray et al. 2011 Davidson et al. 2016 Growcott et al. 2016 Moser et al. 2016, 2017 McClary 2018
Vessel speed The transit speed of commercial and recreational vessels. Some vessel types are inherently slow moving.	Slow moving vessels (5-10 knots) usually contain a greater number and diversity of biofouling organisms, compared to faster vessels. Faster speeds can reduce already attached biofouling assemblages, but some organisms are more resilient to hydrodynamic drag forces than others. Some species can persist at speeds of up to 18-20 knots.	Foster & Willan 1979 Carlton & Hodder 1995 Minchin & Gollasch 2003 Coutts & Taylor 2004 Coutts & Forrest 2007 Davidson et al. 2008a, 2009 Coutts et al. 2010a,b Sylvester et al. 2011 Schimanski et al. 2016 Kauano et al. 2017 McClary 2018
Duration of service Frequency and duration of port durations, and lay-up or idle periods.	Longer periods of inactivity are usually associated with increased accumulation of biofouling communities because the fouling prevention properties of AFCs are less effective under stationary conditions. Generally, regarding idle periods, recreational vessels pose a higher relative biosecurity risk because of their longer lay-up periods, port visits and better maneuverability into sheltered areas, compared to commercial vessels which have limited periods of inactivity, rapid turnaround times in port and are unable to visit some sheltered areas.	Carlton & Hodder 1995 Rainer 1995 Coutts & Taylor 2004 Floerl & Inglis 2005 Ashton et al. 2006 Davidson et al. 2009 Inglis et al. 2010 Bell et al. 2011 Hewitt et al. 2011 Sylvester et al. 2011 Clarke Murray et al. 2012 Lacoursière-Roussel et al. 2012

Factor	Effect	References
	Some slow moving commercial vessels, such as barges, floating cranes, oil rigs and dredges also have longer periods of port residency. Shorter voyages are more likely to accumulate and retain fouling assemblages than longer voyages. Some studies did not find a positive relationship between long port residency times and the level of biofouling (Davidson et al. 2014; Frey et al. 2014; Gewing & Shenkar 2017).	Schimanski et al. 2016, 2017 Davidson et al. 2018, 2020
Transit routes The shipping routes taken by a vessel, including the number of port visits.	Vessels plying tropical regions are usually more heavily fouled than those plying more temperate regions. Voyages within a similar geographic area and latitude are more likely to develop high levels of biofouling, if good practice is not in place. Species adapted to colder waters are more likely to survive and reproduce in warmer environments than species adapted to warmer waters that have been translocated to colder environments (Lewis et al. 2003; Chan et al. 2016). The number of ports or locations visited is generally positively related with the levels of biofouling. Traversing the Panama Canal which contains freshwater can reduce fouling communities on vessels but not eliminate them (section 6.3.2.1.3). Some species can persist through changes in environmental conditions.	Visscher 1928 Jones & Dawson 1973 Brock et al. 1999 Lewis et al. 2003 Minchin & Gollasch 2003 Coutts & Taylor 2004 Davidson et al. 2009 Inglis et al. 2010 Sylvester et al. 2011 Davidson et al. 2012 Lindholdt et al. 2015 Chan et al. 2016 Gewing & Shenkar 2017 McClary 2018 Miller et al. 2018

6.2.1 Vessel design

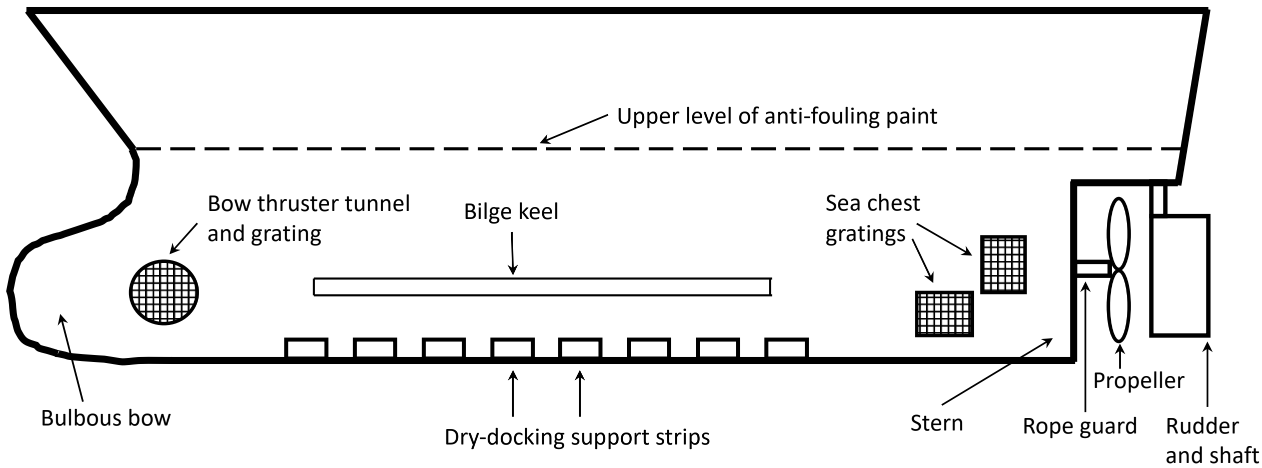
6.2.1.1 Niche areas

Marine vessels are built to serve a particular purpose, whether that is to transport containers from one port to another, or to transport people for recreational purposes. All vessels have areas that are constantly submerged in seawater when in active service, irrespective of their specific design. The largest surface in contact with seawater is the vessel hull, which mostly consists of vertical, curved, and flat-bottom surfaces. Various additional and more heterogeneous surfaces of niche areas protrude (e.g., rudders and propellers) or are recessed from the hull. Recessed niche areas can be hard to access and clean and they are often not covered by anti-fouling coatings but even when they are, protection from these coatings can rapidly degrade (Coutts & Dodgshun 2007; Inglis et al. 2010; Lacoursière-Roussel 2013). Or, if coatings were applied, they may not be effective because the same coating that was applied to the hull was also applied to the niche areas.

The presence, size, complexity and number of niche areas varies depending on vessel type and size (DF 2009; Lacoursière-Roussel 2013). For example, a study quantifying the extent of niche areas on commercial vessels showed that passenger vessels had the highest proportion (27%) of niche areas relative to the total wetted surface area, followed by tugs (25%), fishing vessels (21%) and bulk carriers and tankers (7-8%). Thruster tunnels contributed to >50% of the total niche area on passenger vessels and tugs (Moser et al. 2017). The size of niche areas is related to the overall size of a vessel. This relationship matters in terms of biosecurity risk because larger vessels have a greater total wetted surface area, and therefore more surface available for fouling organisms to attach to, on the hull and in niche areas. For example, the size of niche areas of bulkers is approximately 3.5 times greater than that of fishing vessels and provides about 5 km^2 more surface area for attachment and colonisation by fouling organisms (Moser et al. 2017).

Niche areas on a vessel hull include (Figure 10):

- bulbous bow;
- thruster tunnels;
- bilge keels;
- sea chests, including gratings and internal seawater systems;
- dry-docking support strips;
- propeller;
- rudder; and
- rope guard (Coutts & Taylor 2004; Inglis et al. 2010).



Modified from Coutts & Taylor 2004 and Inglis et al. 2010

Figure 10: Vessel hull and niche areas

Some vessels have a **bulbous bow**, an extension of the hull below the waterline. Its main purpose is to create a low-pressure zone to reduce or eliminate the bow wave which creates drag. The installation of **bow thrusters**, transverse tunnel propulsion units at the bow, provides effective manoeuvring capability for large vessels, especially in confined waters. Transverse thrusters can also be installed at the stern of a vessel. In general, transverse propulsion units are most effective when the vessel is stationary but lose effectiveness with speed (Carlton 2012).

Bilge keels are long narrow keels mounted on the turn of the bilge to provide hydrodynamic stability and protect the vessel against roll. They are the simplest form of stabiliser. Bilge keels provide hull roll damping, especially at low speeds but also increase hull resistance in calm waters (Perez 2005).

Sea chests are cavities in a vessel hull that house the openings to the internal seawater system (Figure 7). They are fitted with gratings which prevents large debris from entering the sea chests during ballast pumping. Sea chests help increase the efficiency of pumping seawater into the internal pipes by providing a motionless reservoir of water for ballast, engine cooling and fire suppression (Coutts & Dodgshun 2007; Growcott et al. 2016).

Dry-docking support strips (DDSS) are areas along the bottom of the hull where blocks are placed to provide support when the vessel is stationary in a dry-dock. As the areas of the hull covered by the dry-dock strips are not accessible during dry-docking, these areas may remain free of any anti-fouling coatings (Piola & Conwell 2010).

Propellers are ship propulsion devices that come in many forms. The most common type on commercial ships are fixed pitch propellers, also named screw propellers (Moser et al. 2017). Fixed pitch propellers are used on bulk carriers, merchant and naval vessels, and on high-speed patrol craft. Propellers vary in size, material used and number of propeller blades (Carlton 2012). They are connected to the hull via a propeller shaft which is usually surrounded by a shaft tunnel to avoid leakage of water into these compartments (Mandal 2017). Biocidal anti-fouling coatings are rarely applied to propellers because the paint erodes quickly under the high shear conditions and causes uncontrolled release of biocides (Karabay 2011; AkzoNobel 2020b).

Propeller shaft casings are protection barriers for propeller shafts that shield them against line or net entanglement but they are also prone to fouling by exotic marine species (CDS 2020a). Rope guards are blades attached to the shaft casing, cutting any entangled ropes or nets.

Rudders are actuators on a vessel, they force a control action. Most surface vessels use rudders to correct the heading of the vessel, but rudders also induce roll motion in some vessels. On merchant vessels, rudders are usually located at the stern of the vessel, behind the propeller (Perez 2005). Other propulsion systems do not have rudders, for example, azipod propulsion systems consist of a case that contains a propeller. The case can be rotated to change the direction of the vessel (Veneri et al. 2012).

6.2.1.2 Fouling of niche areas

Niche areas have been described as hotspots of biofouling accumulation (Davidson et al. 2016) as biofouling abundance tends to be greater on niche areas than on the main hull of vessels (Coutts & Taylor 2004; Hopkins & Forrest 2010; Inglis et al. 2010; Clarke Murray et al. 2011; Davidson et al. 2009, 2012; Lacoursière-Roussel et al. 2012). Davidson et al. (2014) showed that particular components of niches differed significantly in biofouling percent cover and advocated for extending sample stratification beyond niche area to sub-niche area.

The uniform areas of the hull are usually relatively clean of fouling organisms due to effective anti-fouling coatings and greater hydrodynamic forces. However, significant fouling can be present in:

- areas protected from the constant laminar flow of water that can remove fouling organisms: sea chest gratings, surrounding intake pipes, bow thruster tunnels, and rope guards;
- areas with unpainted surfaces: cathodic protection nodes, propellers and propeller shafts, rudder stocks and DDSS;
- areas where anti-fouling coatings are damaged and ineffective because of high turbulence and cavitation: propeller stocks, rudders, intake grates, bilge keels, sea chests and around bow thrusters;
- areas where anti-fouling coatings are ineffective because they have reached the end of their service life: DDSS;
- hard to access areas where anti-fouling coatings were applied inadequately: sea chests, sea chest gratings, and box coolers; and
- complex appendages or equipment: sea chests, box coolers, and emergency propulsion units (Lewis 2002; Coutts & Taylor 2004; Coutts & Dodgshun 2007; Lewis & Coutts 2009; Piola & Conwell 2010; Clarke Murray et al. 2011; Growcott et al. 2016).

A study of biofouling on merchant vessels in New Zealand showed that propellers had no anti-fouling coating, whereas the bulbous bow often had damaged paint and the bilge keel, rudder, rope guard and sea chest gratings were covered frequently with ineffective anti-fouling coatings. This study found the highest levels of biofouling on DDSS and sea chest gratings (Coutts & Taylor 2004). While DDSS are technically not niches because they are not protrusions or recesses, they are still considered a niche area (Davidson et al. 2016). As DDSS often remain free of any anti-fouling coatings they can be hotspots of biofouling. For example, Piola & Conwell (2010) found that among different niche areas on international fishing vessels arriving in New Zealand, fouling biomass and species numbers were consistently highest on DDSS. Inglis et al. (2010) compared the extent of biofouling among different types of niche areas on vessels arriving into New Zealand. Fouling was observed more frequently and in greater numbers on DDSS compared with other parts of the general hull surface, but this pattern was not consistent among vessels as most of the variation in biofouling biomass and species richness was related to vessel-to-vessel differences. At the same time, fouling on DDSS was not very common when compared to other niche areas such as gratings and bow thrusters, which were the most common places for biofouling to be observed (Inglis et al. 2010). Similarly, McClary (2018) reported that DDSS were among the least fouled niche areas. However, fouling organisms do attach and colonise DDSS, therefore it is important to apply anti-fouling coatings. If possible, the positions of support blocks should be varied at alternate dry-dockings, so that anti-fouling coatings can be applied to areas not touched by blocks (Coutts & Taylor 2004; Georgiades et al. 2018). Re-floating and shifting the position of vessels during the same dry-docking does not happen often because of the associated costs (Davidson et al. 2016).

On some vessel types, thruster tunnels contribute to more than 50% of the total niche area, but their status as hotspots of biofouling may be underestimated because in-water cleaning of thruster tunnels can be ineffective and a lower priority (Moser et al. 2017). A survey of biofouling on containerships supports this assessment. Macroscopic biofouling was observed most frequently on rudders, stern tubes and bow thruster gratings (Davidson et al. 2009). Gratings over sea chests and thruster tunnel openings were found to be the most heavily fouled niche areas in a survey of commercial vessels arriving into Australia (McClary 2018). Anti-fouling coatings applied to thruster tunnel openings should be able to withstand cavitation damage (Georgiades et al. 2018). All of the studies cited above did not assess internal niche areas.

Accumulation of fouling species in sea chests is likely due to inadequate biocide release because of either (i) turbulent water flow that causes rapid polishing and exhaustion of anti-fouling coatings, or (ii) low flow in static pockets similar to that of laid-up vessels, leading to insufficient release of biocides as the coating does not polish effectively under reduced hydrodynamic flow (Coutts & Taylor 2004; Coutts & Dodgshun 2007). If the effectiveness of the anti-fouling system in internal niche areas is compromised because of these reasons, or if the system is not suitable for that niche area, then biofouling communities can progress towards tertiary levels of biofouling. Sea chests can contain a number of exotic marine species including adult mobile organisms and have the potential to transfer and disperse these species over great distances (Coutts et al. 2003; Coutts & Dodgshun 2007; Frey et al. 2014; Gewing & Shenkar 2017). Biofouling assemblages within internal niche areas can also act as 'microhabitat engineers' by providing a surface matrix that other fouling organisms find suitable for attachment and growth (Davidson et al. 2009). Steam blow-out pipes can be fitted within sea chests to prevent and minimise biofouling growth. Suitable anti-fouling coatings should be applied on external surfaces of these pipes and associated holding brackets (Georgiades et al. 2018).

The most effective and durable strategy to minimise fouling of niche areas is to consider the issue of biofouling at the initial design and construction of a vessel. The following recommendations provide examples for adaptation that should be taken into consideration (IMO 2011; Georgiades et al. 2018):

- exclude small niches and sheltered areas if possible;
- design round and/or bevel corners, gratings and protrusions for better application of anti-fouling coatings;
- minimise the size and number of sea chests and fit a MGPS;
- fit steam blow-out pipes within sea chests;
- reduce bends and kinks in internal seawater cooling systems and choose appropriate material; and
- design components that can be easily accessed for inspection, cleaning and maintenance (e.g. hinge gratings for diver access, retractable fittings and equipment).

6.2.2 Vessel speed

Vessel transit speed is part of the operating profile of a vessel, which can affect the successful translocation of exotic marine species. Marine vessels range from mobile oil platforms and slow moving vessels (e.g. barges, tugs, recreational vessels, fishing vessels, oil exploration rigs, floating dry-docks) to faster moving ferries and naval vessels. In general, slow-moving vessels (5-10 knots; Hopkins & Forrest 2010) contain a greater number and diversity of biofouling organisms (on both hull surface and niche areas) capable of survival in a recipient location because they are exposed to hydrodynamic drag forces that are considerably less than on faster-moving vessels (Foster & Willan 1979; Carlton & Hodder 1995; Minchin & Gollasch 2003; Coutts & Taylor 2004; Coutts & Forrest 2007; Davidson et al. 2009; Coutts et al. 2010a,b; Sylvester et al. 2011; McClary 2018). However, other factors also play a role, such as the operating profile and the function of anti-fouling coatings. Slow-movers tend to spend extended periods in a recipient environment, increasing the window of opportunity for invasion by transported organisms (MAF 2010).

Fouling organisms that are usually found on vessels struggle to attach to substrates at speeds of more than 4-5 knots (Jenner et al. 1998; Almeida et al. 2007; Lindholdt et al. 2015). Many modern vessels travel at >20 knots which would inhibit attachment of fouling organisms at these speeds thus attachment and settlement probably happens in port regions where vessel speeds are lower or when ships are anchored or berthed (Minchin & Gollasch 2003). Species attachment is also easier in protected niche areas where hydrodynamic forces are lower (Coutts et al. 2003). Since the global financial crisis of 2008-09 many shipping companies have adopted cruising at reduced vessel speed to save fuel. Vessels operating at reduced speed practice what is known as 'slow steaming' (18-20 knots) or 'extra slow steaming' (15-18 knots)(Tezdogan et al. 2016; Rodrigue 2020). Cruising at these low speeds (20-25 knots) may lead to unintended consequences such as increased levels of biofouling on vessel hulls and niche areas (Wiesmann 2010; Mander 2017). Some coatings manufacturers have already reacted to this trend and offer AFCs that can be used for slow steaming vessels (Hempel 2019; Jotun 2020b).

Morphology of biofouling organisms can determine whether vessel speed affects their survival through transit (Coutts et al. 2010a). Vessel speeds of 5 and 10 knots had little effect on species richness of attached biofouling assemblages but speeds of 18 knots reduced richness by 50%. Some organisms were more resilient to hydrodynamic drag forces, for example those with hard calcareous body structures, low-profile encrusting forms and/or flexible morphologies. However, even soft bodied solitary ascidians remained largely unaffected by speeds of 18 knots. In addition, a settlement plate experiment found no influence of flow speed or treatment duration on survival of the sessile bryozoan *Bugula neritina,* exposed to 6 and 18 knots for 2 and 8 days (Schimanski et al. 2016). In a drag experiment using settlement plates, the cover or number of individuals of different fouling organisms decreased with increasing speed but at 20 knots species were still able to persist and survive transport (Kauano et al. 2017).

Species settlement and biofouling accumulation happen gradually on active vessels and vessel speed has an influence on succession and the observed biofouling assemblages (Coutts et al. 2010b). Faster vessels are likely to 'select' for fouling communities that can tolerate greater hydrodynamic drag forces (e.g., hard, solitary, encrusting taxa) but translocation success does not necessarily mean successful establishment of these more drag resistant exotic marine species in a recipient region (Coutts et al. 2010b; Sylvester et al. 2011; Schimanski et al. 2016).

Davidson et al. (2008a) reported a scenario where slow vessel speed contributes to biosecurity risk. In the USA obsolete vessels are often towed to another location for disposal. Usually these vessels are at the extreme end of the biofouling spectrum as they have been anchored for long periods (with anti-fouling paints past their service life and non-functional MGPSs) before being towed. In a study of biofouling assemblages of obsolete vessels before and after transfer to a disposal location, tow speeds of two vessels (an oil tanker and a transportation vessel) were slow and averaging 6.4 knots. When these vessels reached their destination the extent of biofouling was reduced but, unexpectedly, species richness had increased, indicating that additional settlement by new species took place during the slow voyage in open and coastal waters (Davidson et al. 2008a).

While the translocation of high numbers of biofouling organisms on the vessel hull is much more likely on slow-moving vessels in comparison to fast-moving vessels the survival rate of fouling organisms will also depend on environmental influences during transit (Section 6.2.4).

6.2.3 Duration of service

Another aspect of the operating profile of a vessel is its activity pattern, which includes times when it is being stationary and inactive, for example when laid up in open anchorage or berthed at a port. Longer residency times in ports and marinas have been associated with increased accumulation of biofouling, for both commercial and recreational vessels (Carlton & Hodder 1995; Coutts & Taylor 2004; Floerl & Inglis 2005; Ashton et al. 2006; Sylvester et al. 2011; Davidson et al. 2018). Soluble matrix and contact leaching coatings are more effective than FRCs at inhibiting biofouling growth while a vessel is laid-up (Holm et al. 2003; Scianni et al. 2019). This is because some vessel activity is needed to induce self-polishing and release of biocides, or to remove attached fouling organisms from surfaces painted with FRCs by hydrodynamic drag. Although two recent studies (Davidson et al. 2014; Frey et al. 2014) did not find a positive correlation between longer port residency times and the level of cover of biofouling, there are reasons why this may not be widely applicable. The first study surveyed vessels arriving to Californian ports. The lack of effect of long port residency on biofouling levels in this study could have been due to the exposure of marine organisms to freshwater in ports and canals (Davidson et al. 2014), which would reduce their cover as a result of death by osmotic shock (Section 6.3.2.1.3 – freshwater immersion). The other study, investigating fouling abundance and species richness in sea chests of commercial vessels in Canada, attributed the lack of a positive correlation to limited data on port durations and anti-fouling systems (Frey et al. 2014).

Biofouling can quickly accumulate on the hulls and niche areas of inactive vessels. An experimental setup in two marinas on the East Coast and the West Coast of the USA tested the relationship between the duration of stationary periods and the accumulation of biofouling using fouling panels. In this study, AFCs were effective in preventing biofouling on test panels during static conditions at one test site, but after 60 days macrofouling cover had reached 20% at the other test site. Biofouling levels were high (>85% cover) on uncoated control panels after 28 days of immersion under static conditions (Davidson et al. 2020). FRCs were less effective in preventing biofouling but the observed high levels of biofouling (>70% cover) on one test site after 45 days may have been due to macrofoulers gaining foothold on backing PVC plates during the experiment (Davidson et al. 2020).

The varying activity patterns of different vessel types may translate to different levels of biosecurity risk. Recreational vessels are considered higher risk in a relative sense because of their long lay-up periods, slow and roaming voyages (Chebaane et al. 2019; Cabral et al. 2020). Commercial vessels may pose less of a relative biosecurity risk based on their rapid turn around and limited periods of inactivity (Bell et al. 2011). However, in general, biofouling associated with *all* vessel types poses a risk to natural, economic and social values (Inglis et al. 2010; Georgiades et al. 2020).

Statistical evidence for the difference in activity patterns between commercial and recreational vessels and also among different types of commercial vessels is available from targeted research studies or productivity reports published by government agencies or intergovernmental bodies. For example, Inglis et al. (2010) reported strong differences in activity patterns when comparing commercial vessels with recreational vessels arriving into New Zealand. On average, yachts spent longer time in port and at sea, and had longer lay-up periods compared with commercial vessels. Yachts also visited fewer ports and tended to arrive from a smaller range of international bioregions. Comparing different types of commercial vessels showed that bulk carriers were inactive for longer periods of time and also spent more time in ports and at sea than the other types of commercial vessels (Inglis et al. 2010; Davidson et al. 2018). Similarly, slow moving vessels such as barges, floating cranes and oil rigs may be inactive in ports for longer periods of time and are not regularly cleaned (Rainer 1995). Dredges are also believed to be high risk because of their slow speeds and long periods of port residency (more than 30 days) (Hewitt et al. 2011), on top of the biosecurity risk they pose due to their close interaction with the seabed.

Passenger ships, container/general cargo ships, RoRo vessels, car carriers and reefers had the fastest port turnaround times, ranging from 0.9 to 1.89 days (Inglis et al. 2010). Looking at a worldwide dataset, in 2018, a typical ship call had a turnaround time of 0.97 days (median of top 25 economies, 0.7 days for container ships). Dry bulk carriers, in contrast, spent 2.05 days in port, liquid bulk carriers 0.94 days and other carriers between 1.02-1.11 days (UNCTAD 2019). Containerisation, optimised port infrastructure and operations, and modern technology for maximising loading efficiency have resulted in containerships spending less than a day and usually less than 12 hours in a port (Davidson et al. 2009; Frey et al. 2014; UNCTAD 2019) but that depends on the geographic location of the port. The median ship turnaround time was 30.9 hours for Australia's five container terminals from January to June in 2019. The performance among terminals varied, with median ship turnaround times ranging from 20.7 to 36.7 hours during that period (BITRE 2019).

Sylvester et al. (2011) developed a simple modelling approach for predicting the extent and intensity of biofouling on commercial vessels in Canada. As part of the study, 40 transoceanic commercial vessels were surveyed, including bulk carriers, container ships, cargo carriers, and oil and chemical tankers, RoRo cargo vessels, and one cable layer. Time in port and time since last application of anti-fouling coatings were significant covariates for propagule and colonization pressure in the model.

A number of studies have investigated the influence of lay-up periods on the extent of biofouling on recreational vessels. Floerl & Inglis (2005) found that the duration of a lay-up period within a marina was only weakly correlated with biofouling abundance on recreational boats. However, the influence of this variable was masked by the effect of anti-fouling coatings as the most heavily fouled boats were those that had not had anti-fouling coatings applied for >20 months and had stayed inactive in a marina for >8.5 months. Pelletier-Rosseau et al. (2019) conducted boat fouling surveys of recreational boats in Canada and dry-dock interval (i.e., active and inactive time in water) was the strongest predictor of biofouling state in this study. Using a wider geographical scope, Lacoursière-Roussel et al. (2012) compared biofouling on recreational boats in Canada with boats in New Zealand. They deemed lay-up periods to be a more reliable predictor of boat fouling than time since last anti-fouling based on the assumption that most niche areas are not treated with anti-fouling coatings. Clarke Murray et al. (2013) found that the time in water of recreational boats in Canada had a positive relationship with macrofouling, boats that were stored in water for longer had greater chances of macrofouling. In line with the other studies, yachts in Scotland that spent a long time stationary in port, with less activity in the last 12 months compared to other yachts, were more likely to have macrofouling species attached to their hull (Ashton et al. 2006).

A study examining biofouling on recreational, commercial and military vessels in response to different variables did not find an effect of lay-up period on the abundance and richness of fouling assemblages. Military vessels had the highest average number of fouling individuals and species on hulls and niche areas which was attributed to inadequate cleaning procedures for this type of vessel (Gewing & Shenkar 2017).

6.2.4 Transit routes

Vessel transit routes contribute to biofouling on marine vessels, starting from the time of the last dry-docking or cleaning. Voyage pattern includes the number of ports visited and the shipping routes from the port of first call to a vessel's destination.

The number of ports visited is a factor that may influence biofouling. A predictive model using transoceanic vessels in Canada compared two harbours and showed that vessels that had visited more regions arrived with a higher abundance and number of fouling species. This is likely the result of exposure to a greater variety of marine communities (Sylvester et al. 2011). A survey of international commercial vessels arriving in Australia determined a strong correlation between the number of port of calls since the last application of an anti-fouling coating and the fouling rating of hull and external niche areas combined (McClary 2018). However, the results were skewed by low fouling ratings of hull areas of vessels that visited a high number of different ports. Inglis et al. (2010) found a positive relationship between the predicted probability of presence of established exotic marine species in New Zealand and the number of ports commercial and recreational vessels visited since being anti-fouled, with a sharp increase when commercial vessels had visited more than 30 ports. The risk factor of 'average number of days spent in port' was stronger for recreational vessels (Georgiades et al. 2020). Because each port has its own pool of species, vessels visiting a number of different ports will inevitably develop a fouling assemblage that can vary greatly within the same vessel and between vessels (Inglis et al. 2010) but for recreational boats with longer residency time in ports fouling assemblages are likely to reflect the assemblages of the resident biota in the boat's home marina (Floerl & Inglis 2005). Recreational vessels may visit a number of diverse locations, but also areas that larger vessel cannot access. Recreational vessels potentially can transfer exotic marine species to sheltered areas such as bays and lagoons (Chebaane et al. 2019; Cabral et al. 2020). The naturally slow moving water in some bays and lagoons can lead to increased water temperature and salinity which could provide suitable conditions for successful establishment of some exotic marine species (Ros et al. 2015; Chebaane et al. 2019).

Vessels that move within a similar geographical area, in which environmental conditions are comparable or identical can develop high levels of biofouling (Visscher 1928). For example, Coutts & Taylor (2004) found that vessels that traded domestically throughout New Zealand or across the Tasman Sea had the highest mean species richness and percentage cover of fouling organisms, compared to trans-equatorial vessels. Similarly, one outlier with a significantly shorter voyage range in a set of container ships surveyed had the highest levels of biofouling (Davidson et al. 2009). These examples indicate that, compared with transit routes across latitudes (between hemispheres), voyages that stay within the same latitude may be less stressful for attached fouling organisms as they are exposed to less physiological stress, for example changes in temperature (Minchin & Gollasch 2003). Interestingly, a predictive model by Seebens et al. (2013) found that the invasion probability is highest for intermediate geographic distances (8,000–10,000 km) between donor and recipient ports, a finding which reportedly matches field observations.

Trans-latitudinal voyages are usually associated with significant fluctuations in temperature and salinity (Davidson et al. 2008a). Transit routes that require vessels to frequently transit inter-ocean corridors such as the Panama and Suez Canals may affect the degree of biofouling as these passages expose fouling organisms to potential physiologically stressful conditions. Organisms are exposed to warm freshwater (Jones & Dawson 1973) during transit through the Panama Canal and to warm water and marine hyper salinity during transit through the Suez Canal (Miller et al. 2018). These biologically stressful environments may filter or kill a proportion of the species attached on vessel hulls, however the effects on biota are not yet fully understood (Miller et al. 2018).

In this context, it is more likely for marine species from a cold-water ocean like the Southern Ocean to be translocated and establish in northern environments than it is the other way around. Marine species adapted to colder waters can survive and reproduce at water temperatures that are higher than their normal abiotic habitat conditions, but species from lower latitudes may struggle to invade colder environments because of the physical differences between the donor and recipient environment (Lewis et al. 2003). A study of biofouling on vessels transiting to and from the Arctic showed that species richness and abundance of fouling assemblages on vessels strongly decreased, by 70% and 80% respectively, after transit from temperate to arctic waters (Chan et al. 2016; sampled ships avoided contact see ice, consequently no effects of ice scouring on biofouling assemblages were observed). In this case, niche areas were not able to protect biofouling taxa from harsh arctic conditions. Despite the poor survivorship of fouling organisms, there is still the risk of transporting exotic marine species to the Arctic via vessel biofouling (Chan et al. 2016).

At the other end of the spectrum of seawater temperatures, vessels that visit ports in tropical regions are usually more heavily fouled (Davidson et al. 2014), and in a shorter time, than those that ply more temperate zones (Visscher 1928). Warmer temperatures during spring and summer of temperate zones promote faster fouling growth on inactive vessels than in the colder autumn and winter months (Visscher 1928). Warmer temperatures also typically lead to greater biofouling of vessels that are in service (Lindholdt et al. 2015). Gewing & Shenkar (2017) observed an increase in ascidian abundance and richness on niche areas of military vessels with rising seawater temperature (up to the level of tropical waters).

Vessel origin was used as a variable in a study in Canada and indicated whether a vessel travelled domestically or internationally before arriving at a port. Vessel origin did not influence taxonomic richness or abundance of fouling species in sea chests of dry-docked commercial vessels. However, sea chests of international vessels in this study contained significantly more non-indigenous species than domestic vessels (Frey et al. 2014). A study in a French port showed that the area of origin did not influence the assemblage of macroalgae species on hulls of commercial ships as the macroalgae species found were already ubiquitous in ports (Mineur et al. 2007).

Fouling species are capable of surviving long-distance transport via commercial vessels along shipping routes as evidenced by exotic species having established either side of the same ocean within the same hemisphere, (Minchin & Gollasch 2003). The likelihood of survival depends on the type of fouling species and their ability to sustain themselves during long transit. There is a greater concentration of food for biofouling organisms in inshore waters relative to the open ocean (US Congress 1987) but access to the food can be challenging while attached to a ship. Water filtering feeders such as ascidians may have the physical ability to remain attached to hull surfaces during trans-oceanic journeys, but they may not be able to survive it if their filter-feeding time is limited or restricted by increased water velocity (Clarke Murray et al. 2012; Schimanski et al. 2017). The effects of long voyage times on fouling organisms can lag and be observable after arrival like in the case of *Bugula neritina* colonies in a settlement plate experiment. Longer and faster voyage reduced post-voyage growth rates in this fouling species (Schimanski et al. 2016). In general, commercial vessels that regularly undertake shorter domestic voyages are more likely to accumulate and retain fouling assemblages than those vessels that travel over longer distances (Coutts & Taylor 2004; Davidson et al. 2009). Furthermore, vessels that undertake successive short intra-coastal voyages and have short residence periods may be able to transfer viable organisms that are more reproductively successful and able to establish than those transported on vessels with longer voyages and residency periods (Schimanski et al. 2017).

Transit method (i.e., vessels entering Australia in water or as cargo out of the water) will also influence the survivorship of exotic marine species that are translocated. The survivorship is likely to be greater for vessels that transit to Australia in water. However, dry transportation does not eliminate the risk because some species can survive periods of desiccation. For example, in one instance Asian green mussels *Perna viridis* survived a two month journey on a jack-up barge transported on a heavy lift vessel from north-east Asian to North Queensland (Andersen et al. 2006). Though the jack-up barge was imported out of the water as cargo on the heavy-lift vessel, Asian green mussels had survived the voyage of approximately two months. Therefore, such a method of transport, without biofouling management, does not eliminate the risk of exotic marine species being translocated. Cleaning the vessel once it was out of water would have reduced the biosecurity risk.

6.3 Management practices

Environmental conditions in ports and during voyages, as well as vessel characteristics and operating profiles contribute to the attachment and transport of fouling organisms on vessel hull surfaces and niche areas. The most effective risk management strategy for dealing with invasive exotic marine species through biofouling is prevention because response measures to an invasion are often time consuming and expensive (Davidson et al. 2008b), and rarely result in successful eradication (Georgiades et al. 2020). However, while measures to reduce biosecurity risk are preferably done preventatively or proactively, they are also done reactively, in response to biofouling (Scianni & Georgiades 2019; Georgiades et al. 2020). Management practices include the application or installation of anti-fouling systems, biofouling surveys, vessel maintenance and in-water cleaning or treatment.

In this report proactive and reactive measures are defined as follows:

Proactive measures: are activities undertaken to prevent or reduce the accumulation of microfouling on vessels to minimise the likelihood of biofouling advancing to secondary and tertiary stages. In this document, proactive measures refer to all activities that vessel owners and operators can undertake before vessels arrive at an Australian port.

Reactive measures: are activities undertaken to remove or treat biofouling on vessel hulls and niche areas that has already advanced to the macrofouling stages. Reactive measures are not planned in advance and are usually taken as a result of levels of fouling impacting vessel operations or are initiated by a regulator to manage risk. Reactive measures may need to be applied to vessels that arrive in Australia and are identified as high risk due to their excessive biofouling levels.

6.3.1 Proactive measures

Proactive measures are considered best practice for ongoing hull maintenance because vessel owners or operators act in anticipation of future fouling problems and try to avoid the accumulation of macrofouling species on vessel hulls and niche areas (Georgiades et al. 2018). Ideally, proactive measures are undertaken before vessels start their journey to or from Australia.

Proactive measures include:

- biofouling management plans and record books;
- application of anti-fouling coating systems;
- installation of a MGPS;
- hull grooming; and
- treatment of internal seawater systems.

6.3.1.1.1 Biofouling management plans and record books

Most of the following methods are not fully effective individually and should be used together to manage a vessels biosecurity risk. The IMO guidelines for the control and management of biofouling on ships recommends that vessel owners develop a biofouling management plan and keep a biofouling record book (IMO 2011).

The *biofouling management plan* should describe the biofouling management measures to be undertaken on a ship, form part of the operational documentation and be updated as necessary. The plan should be vessel specific and address, among other things, the following (IMO 2011):

- relevant parts of the Guidelines;
- details of the anti-fouling systems and operational practices or treatments used, including those for niche areas;
- hull locations susceptible to biofouling, schedule of planned inspections, repairs, maintenance and renewal of anti-fouling systems;

- details of the recommended operating conditions suitable for the chosen anti-fouling systems and operational practices;
- details relevant for the safety of the crew, including details on the anti-fouling system(s) used; and
- details of the documentation required to verify any treatments recorded in the biofouling record book.

The *biofouling record book* should record details of all inspections and biofouling management measures undertaken on the ship and be kept on board at all times. This can assist the vessel owners and operators in evaluating the efficacy of the specific anti-fouling systems and operational practices on the ship. The record book could also assist interested State authorities in quickly and efficiently assessing the potential biofouling risk of the ship, minimising delays to ship operations.

Information that should be recorded in a biofouling record book includes the following (IMO 2011):

- details of the anti-fouling systems and operational practices used (where appropriate as recorded in the Anti-fouling System Certificate), where and when installed, areas of the ship coated, its maintenance and, where applicable, its operation;
- dates and location of dry-dockings/slippings, including the date the ship was re-floated, and any measures taken to remove biofouling or to renew or repair the anti-fouling system;
- the date and location of in-water inspections, the results of that inspection and any corrective action taken to deal with observed biofouling;
- the dates and details of inspection and maintenance of internal seawater cooling systems, the results of these inspections, and any corrective action taken to deal with observed biofouling and any reported blockages; and
- details of when the ship has been operating outside its normal operating profile including any details of when the ship was laid-up or inactive for extended periods of time.

The biofouling management plan and record book may be stand-alone documents, or integrated in part or fully, into the existing ships' operational and procedural manuals and/or planned maintenance system.

6.3.1.1.2 Application of anti-fouling coatings

The widespread use of anti-fouling coating systems, biocidal and non-biocidal, has played a role in reducing the contribution of the vessel biofouling pathway to the introduction and establishment of invasive species (Bax et al. 2003). While anti-fouling coatings cannot eliminate biofouling, vessel operators apply them to minimise settlement and growth of fouling organisms on vessel hulls and niche areas (Georgiades et al. 2018, section 6.1). Incidental amounts of macrofouling on vessels are common, even if best management practices are applied (Georgiades & Kluza 2017).

Biocidal and non-biocidal anti-fouling coatings are only effective for a particular period of time (Section 5.1.1). After that, their effectiveness in minimising biofouling decreases rapidly and they need to be replaced. Vessel operators determine the planned in-service period of their vessels and schedule dry-dockings guided by IMO conventions relating to safety and environment protection (Floerl et al. 2010). For commercial vessels, it is important to choose appropriate anti-fouling coatings that match the planned dry-docking intervals and consider vessel activity patterns, expected coating longevity, design and construction of the vessel, and planned maintenance (DE/MPI 2015; Georgiades et al. 2018). Selecting an inappropriate coating may lead to excessive accumulation of biofouling, increased release of biocide, and more frequent maintenance activities. Operators of commercial vessels usually plan for 5-year dry-docking intervals but a survey of 135 larger vessels in Hawai'i (mainly passenger vessels, tankers, container ships, tugs and barges) showed that most vessels had a planned maintenance interval of between 2.5 and 3.5 years. This may have been due to prescribed special survey intervals by the vessels' classification societies rather than AFC service life, but firm conclusions could not be drawn due to the small number of vessels in this dataset, n=57 (Tennant et al. 2019). Class surveys of the outside of a vessel's hull in dry-dock should be undertaken with a maximum of 36 months apart, even if the class certificate is valid for five years (IACS 2011). Vessel owners often use these prescribed dry-dock surveys to renew anti-fouling coatings. For recreational vessels, the maintenance schedule is determined by factors other than operational forecasts and logistical constraints (DE/MPI 2015).

The application of anti-fouling coatings requires vessels to be dry-docked. Dry-docking activities are expensive, and opportunities may be limited (Floerl et al. 2010) which puts pressure on the proper application of anti-fouling coatings. When applying anti-fouling coatings to vessel hulls it is important to apply the selected anti-fouling coatings as specified by the manufacturer. This includes preparing the surface and using the correct technique to achieve the coating thickness and ensuring that environmental conditions are conducive to the application of the coating and that the applier of the paint is suitably trained (ABS 2017). Careful surface preparation is essential for achieving the expected service life of the anti-fouling coating. It includes removing the old coating, residual biofilm, biofouling and other contaminations prior to applying the new anti-fouling coating (ABS 2017; Georgiades et al. 2018).

6.3.1.1.3 Installation of a MGPS

MGPSs are systems that are installed on board of a vessel to prevent or minimise biofouling in the sea chests and internal seawater systems of a vessel. Different types of MGPS can be used (Section 6.1.2 Marine Growth Prevention Systems).

6.3.1.1.4 Hull grooming

Hull grooming is the habitual, frequent and gentle underwater removal of microfouling on an in-service vessel with minimal impact to the anti-fouling coating and to pre-empt macrofouling. Grooming prevents or reduces the biofilm and disturbs the fouling at the juvenile and settlement stages, eliminating recruitment and transport of potential invasive marine species (Hunsucker et al. 2019a; Scianni & Georgiades 2019). Light cleaning and removing of the slime layer optimises operational efficiency and may not require full containment of biofouling waste if removal is done to coating manufacturers' specifications and meets local discharge requirements (DE/MPI 2015; Georgiades et al. 2018). Other benefits of hull grooming include increased coating longevity and ship availability, reduced energy consumption and need for reactive hull cleaning, and prevention of transporting exotic marine species (Tribou & Swain 2010; Hearin et al. 2015). Hull grooming can proactively control biofouling and is beneficial for all vessels. For example, vessels that are inactive in ports for long periods of time under high fouling pressures and slow moving ships that are equipped with FR coatings. While mechanical grooming is effective in removing most biofilm, small areas of tenacious low-profile biofilm may persist (Hearin et al. 2015). How effectively grooming can control biofouling on hulls depends on the fouling pressure, the frequency of treatment, the season, the type of grooming tool (e.g. rotating brush) used and the forces imparted by the tool (Tribou & Swain 2015; Hearin et al. 2016). Gentle removal of microfouling should not damage anti-fouling coatings but more rigorous cleaning and removal of mature calcareous fouling can lead to coating damage (Tribou & Swain 2015; Scianni & Georgiades 2019). Weekly groomed surfaces covered with copper ablative coatings showed only minimal loss of coating over a period of six years (Tribou & Swain 2017). Similarly, a one-year study did not find significant wear or damage of AFC or FRC panels that were cleaned bi-monthly/monthly with waterjets during that period, applying adhesion-strength level cleaning forces (Oliveira & Granhag 2020).

A full cleaning of a vessel's hull is expensive and time consuming (Inglis et al. 2012). Hull grooming could save costs for vessel operators if vessels can be maintained over the lifetime of the anti-fouling coating using a hull grooming method. Grooming can be done using small autonomous underwater vehicles equipped with rotating soft push brushes (Schultz et al. 2011; Hunsucker et al. 2019a). Technology for proactive hull grooming is continuously evolving. Jotun, one of the main suppliers of marine coatings, has developed 'HullSkater', an underwater robotics system installed during dry-docking. The fitted system monitors vessel performance and fuel consumption data and predicts the time for an inspection mission which then determines whether a proactive grooming mission is required (Jotun 2020c). Another example is HullBug, a semi-autonomous hull grooming system that disrupts the early signs of biofouling. This robotic cleaner includes a chlorophyll fluorescence sensor that detects fouled patches (Morrisey & Woods 2015; USCG 2016). Shipshave ITCH is a semi-autonomous hull cleaning robot equipped with soft brushes that allows cleaning of the hull while the vessel is in service (Shipshave 2021).

Hull grooming can also be achieved by applying a heat treatment. The Hull Surface Treatment (HST) technology is designed to proactively target the primary stages of biofouling. It uses thermal shock to kill marine slime, algae and weeds and can deal with immature tube worms but not mature biofouling growth such as barnacles. The HST uses hot seawater to sterilize the hull, apparently without damaging the anti-fouling coatings; however use of this system should include consultation with coatings manufacturers (Morrisey & Woods 2015; CDS 2020b).

For recreational vessels with ablative coatings, cloths and pieces of carpet can be used to remove light, soft fouling such as microbial films and small algae (Morrisey & Woods 2015).

6.3.1.1.5 Treatment of internal seawater systems

Proactive treatment of internal seawater systems can be achieved by the following non-toxic approaches. Refer to Jenner et al. (1998) and Grandison et al. (2011) and references therein for more information on these treatments.

- **UV radiation:** is mainly used for sterilisation of treated water as it is most effective against bacterial and planktonic fouling but not established fouling; is better suited as a pre-treatment than a solution on its own for fouling in internal seawater systems; enhances the efficacy of biocides, and requires low maintenance.

- **acoustic energy (ultrasonics)**: pulsed acoustic energy is generated by electrical discharge causing an electrohydraulic shock; inhibits the formation of biofilm and may be able to prevent settlement of fouling species in internal seawater systems; it has limited applicability, and installation of ultrasonic treatment systems is very expensive.
- **low level laser**: laser irradiation in water caused death of diatom and dinoflagellate cells in experimental setup; involves passing of raw water through an irradiation chamber but any surviving fouling organisms after this point require additional treatment; cannot treat established biofouling.
- **engineering and mechanical solutions**: improved filtration mechanisms at seawater intake points may restrict inflow of fouling organisms; application of anti-fouling coatings on internal systems and niche areas may assist in protecting internal systems.
- **design solutions**: for example: reduce the use of small-bore piping which is susceptible to blockage by biofouling; do not use seawater for cooling of equipment; install seawater treatment systems with multiple dosing points throughout the internal seawater network; manipulate flow velocities and turbulence regimes to prevent biofouling.

Investigating the effectiveness of different anti-fouling systems and practices, a study funded by the New Zealand government surveyed a vessel that had an ultrasonic system installed. The ultrasonic transducers were fitted to inboard walls of the box cooler sea chest and to the top of the box cooler. The study found the ultrasonic system to be ineffective in preventing biofouling. The biofilm within the sea chest near the transducers was the same as on other parts of the sea chest wall and the box cooler was covered in macrofouling, dominated by bivalve molluscs (Lewis 2016). Pulsed ultrasound energy has been shown to control the formation of biofilm and reduce its thickness (Bott 2000). However, audible underwater sound emitted by vessels in port seems to attract larvae, promoting their settlement and increasing growth of a number of fouling species (Stanley et al. 2014).

Cloete (2002) suggested the use of Electrochemically Activated (ECA) water to control microbial growth. To 'activate' water, a dilute saline solution passes through an electrolytic cell with an anodic and cathodic chamber separated by a permeable membrane. The result of the treatment is Anolyte, an activated solution, which acts as an oxidising agent with anti-microbial effect. Anolyte affects the bacterial membrane and other functions of the cell. Activated hypochlorous acid solutions, for example, can be 300 times more active than sodium hypochlorite generated by earlier systems (Cloete 2002). However, no commercial solution applying this method seems to be available for ship onboard use.

While there is an established set of proactive measures that the shipping industry has adopted for biofouling management, research into other avenues of biofouling prevention is continuing. The use of short-wave ultraviolet light (UVC, 200 to 280nm wavelength) is a promising approach with the potential to become another proactive measure to prevent biofouling. AkzoNobel, in collaboration with Royal Philips, are aiming to develop UVC LED technology into an economically viable solution for under water fouling prevention (AkzoNobel 2020c). Proof of concept trials have demonstrated that UVC light emitting tiles can achieve total fouling prevention by eliminating all fouling growth including bacteria and slime layer. AkzoNobel have advanced the development of this technology to a point where the fourth generation of prototype UVC light emitting tiles are ready to be tested in situ on the submersed parts of the outer hull and in niche areas of different vessel types (AkzoNobel 2020c).

UVC has also been investigated to improve performance of anti-fouling coatings. Hunsucker et al. (2019b) arranged submerged test panels coated with different anti-fouling coatings (copper, silicone) in a box and exposed them to varying UVC treatments. Panels that were not exposed to UVC were heavily fouled. Continuous UVC exposure damaged copper coatings but panels that were exposed to intermittent UVC treatments showed that the treatment was effective in preventing biofouling recruitment to the copper and FRCs. The most interesting aspect of this research is its potential practical application to areas of vessels that are hard to access and clean, the niche areas. Before that, however, more research into treatment specifications (dosage, exposure time, frequency) and abiotic influences is required (Hunsucker et al. 2019b), as well as considerations about logistics of treatment application.

6.3.2 Reactive measures

Reactive measures are undertaken in response to established secondary and tertiary biofouling present on submerged parts of a vessel. Reactive measures should not be seen as substitutes for earlier or better maintenance practices because they may pose additional biosecurity and chemical contamination risks to the environment from the release of propagules or individuals, and biocides and paint waste, respectively (Scianni and Georgiades 2019). If biofouling is not maintained to an acceptable level, vessels planning to arrive at Australia's border may be identified as high risk pre-border and directed to manage their biosecurity risk associated with biofouling. Different approaches are available to treat or remove macrofouling on hull and external niche areas (Morrisey & Woods 2015) and internal niche areas (Growcott et al. 2017; Cahill et al. 2019c).

6.3.2.1 Hull areas

The maintenance of the underwater parts of a vessel is often referred to as hull husbandry (US EPA 2011). Hull husbandry is initiated in response to marine macrofouling, but it also includes the gentle removal of slime and minor biofouling to prevent macrofouling (Floerl et al. 2010, Section 6.3.1.1.4 – hull grooming). Vessel hulls represent vast areas of uniform surface area that is ideal for biofouling species to colonise. The surface area that fouling species can attach to increases with vessel length (Morrisey et al. 2013). Because of the large area, removal or treatment of biofouling on hull areas is time consuming and means that a vessel is unavailable for active service for a period of time. Controlling hull biofouling is also associated with different types of costs such as for dry-docks, labour and equipment hire, waste removal and new anti-fouling coatings.

Some hull husbandry activities can be undertaken in water, such as hull cleaning, propeller polishing and inspection, but application of anti-fouling coatings is always done out of the water, in dry-dock, slipways or haul out facilities (US EPA 2011; Jacob et al. 2018; Georgiades & Kluza 2020). Reactive measures applied to hull areas include:

- out-of-water maintenance;
- desiccation (dry haulage or dry-dock);
- in-water clean (different methods); and
- time in freshwater.

6.3.2.1.1 Out-of-water maintenance

Apart from applying anti-fouling coatings, dry-docks, slipways and haul-out facilities are used for completing cleaning, repairs and surveys. The onshore removal of biofouling immediately prior to departure from a donor region is the best way to reduce the risk of transferring exotic marine species. This is not practical for commercial vessels, but easier to implement for recreational vessels. A recent national survey of 1,585 recreational boat owners revealed that out of water cleaning is used more often than in-water cleaning in this sector, with 69% of respondents taking their boats out of water for hull cleaning at least once a year. Still, 60% of respondents stated that they cleaned their boat hulls in-water at least once a year (Stenekes et al. 2018), which conforms with the cleaning guidelines in terms of timing (DE/MPI 2015), but appropriate cleaning practices were not always applied (Stenekes et al. 2018). Smaller vessels are often cleaned onshore with handheld scrapers or high pressure water jets (Inglis et al. 2012). The method of rapid high-pressure washing using freshwater can result in inadequate removal of invertebrates inhabiting protected niche areas, especially of ascidians which can survive periods of time out of water (Gewing & Shenkar 2017). But inadequate removal of biofouling holds true for any removal technique because people make errors and they cannot access protected niche areas (Hopkins et al. 2010; Davidson et al. 2018).

Comparing reactive measures undertaken out of water with in-water activities showed that fewer soft-bodied fouling organisms survived haul-out or dry-dock cleaning operations (e.g. water blasting) than they did following in-water manual scraping of vessel hulls (Woods et al. 2007). However, removing vessels out of the water outside the regular service schedule is often not economically feasible or logistically possible for owners and operators of larger vessels (Floerl et al. 2010). Availability of dry-dock facilities is limited, particularly in Australia, and spots need to be booked well in advance (Inglis et al. 2012).

In dry-docks and haul out facilities solid fouling waste can be collected and disposed of in landfill while suspended solids are first settled in tanks and then moved to landfill. The remaining cleaning effluent is either discharged without filtration or filtered and then discharged to the sea or, if nearby, a municipal sewerage system (Woods et al. 2012; Morrisey & Woods 2015; MPI 2017; Scianni & Georgiades 2019).

6.3.2.1.2 Desiccation

Desiccation is the air-drying and killing of marine fouling organisms attached to vessels. The remains of the dead marine organisms need to be removed from the hull to avoid the economic costs of increased friction. Air drying is a simple biosecurity risk mitigation method that requires no chemicals, and if detached fouling waste is captured and disposed properly, it also does not pose risks to the environment or biosecurity. The method of air-drying has also been used elsewhere to control biofouling, such as in power plants, for raw water feed systems, water reservoirs, locked marinas and impoundments (URS 2007).

Different groups of species require different desiccation times until total mortality is achieved. Some organisms are resistant to desiccation, for example oysters, mussels, barnacles, crabs and some green and brown macroalgae (URS 2007, Aquenal 2009a) while some soft-bodied organisms die quickly when removed from water (Inglis et al. 2012). To test the desiccation tolerance of different marine biofouling organisms, an experiment carried out in New Zealand transferred collected oysters to plates that were attached to a wooden frame and placed outdoors in direct sunlight (Hopkins et al. 2016). Ascidian species died within 24 hours. The tested mussel species died after seven days but the oyster species remained viable for up to 16 days. Under controlled conditions the investigated oyster species even remained viable for 34 days. Temperature and humidity played an important role in the success of this method and one conclusion from this experiment was that warm and moist regions are of greatest concern and would require additional treatment such as chemical spraying. Another conclusion was that air-drying for a period three weeks would be sufficient to kill most biofouling, whereby early life-stages are killed first (Hopkins et al. 2016).

To optimise drying conditions, vessel hulls should be located in areas that are well ventilated, sheltered from rainfall and sea spray and preferably of low humidity (URS 2007). The rate at which fouling organisms die when exposed to air depends on environmental conditions (temperature, humidity, rainfall, and direct sunlight) and on the amount of biofouling present on the vessel. If there are large aggregations of biofouling, moisture can be retained within them which allows small fouling organisms to survive (Inglis et al. 2012).

Desiccation is not a feasible option for large commercial vessels over 30m as the cost for prolonged dry-dock duration would be prohibitive (Inglis et al. 2012). It is also impractical for owners of recreational vessels. Inglis et al. (2012) calculated that leaving a recreational vessel on a hard stand for 21 days, as suggested by URS (2007), to kill off fouling organisms would be much more expensive than haul-out and cleaning by water-blasting, which can be done in less than a day.

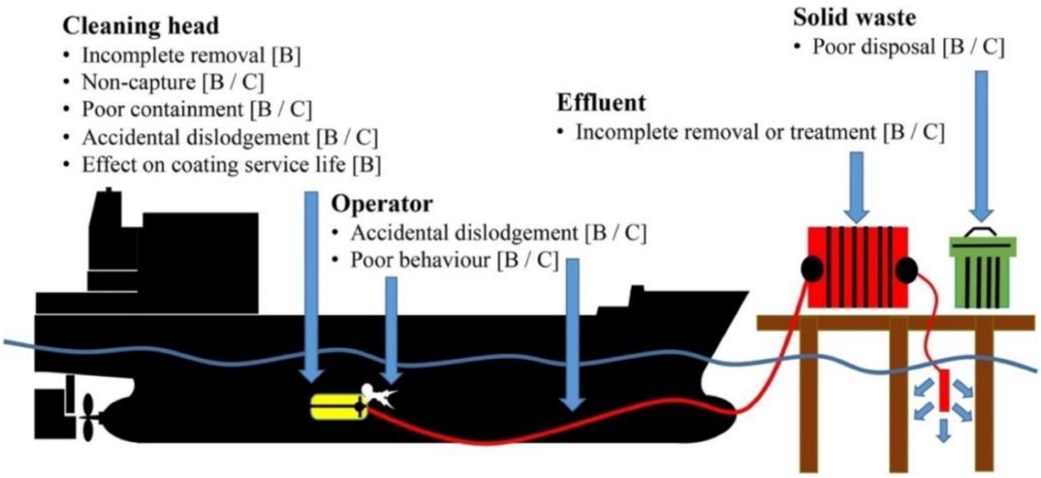
6.3.2.1.3 In-water cleaning

As preventative technology and proactive management practices cannot always keep vessel hulls clean of biofouling organisms most vessel types develop biofouling assemblages between scheduled dry-dockings (Georgiades & Kluza 2017). Consequently, ongoing maintenance of vessel hulls and removal of biofouling is required to extend the life of anti-fouling coatings, reduce biosecurity risk and ensure optimum operational performance. In-water cleaning is a key component of a vessel's biofouling management regime and usually markedly cheaper than shore-based cleaning because of high direct and indirect costs, such as losses in revenue, associated with the latter (Bohlander 2009; Floerl et al. 2010; Morrisey & Woods 2015).

Despite its benefits, in-water cleaning also poses chemical contamination and biosecurity risks to the surrounding marine environment (Morrisey et al. 2013; DE/MPI 2015). During cleaning activities anti-fouling coatings can get damaged and release biocides at elevated rates. Most commercially available in-water cleaning technologies do not capture and contain biological and coating waste released during cleaning activities (Morrisey et al. 2015) but some systems that are able to are operating or under development (Lewis 2020; Tamburri et al. 2020). If detached fouling organisms (including reproductive propagules, Sherman et al. 2020) are not retained, then they may settle on seabeds or adjacent structures or become more widely dispersed by currents (Hopkins & Forrest 2008) and establish in the marine environment (Scianni & Georgiades 2019). The chemical contamination and biosecurity risks associated with in-water cleaning are depicted in Figure 11. If particulate and dissolved metal fractions released from the cleaning head and the effluent are not treated, they can contaminate the environment. Losses of paint flakes or fouled material can happen because of operator fault or equipment shortcomings associated with capturing and treating of cleaning waste or if the cleaning method is inappropriate for the coating being cleaned (Scianni & Georgiades 2019).

In 2015, the Australian and New Zealand governments released voluntary anti-fouling and in-water cleaning guidelines to help jurisdictions and vessel owners and operators to assess the risks posed by in-water cleaning (DE/MPI 2015). Because of the risks associated with in-water cleaning, Australia's position is that 'international vessels clean before they leave, rather than relying on in-water cleaning to manage biofouling on arrival' (DAWE 2020). It is expected that vessels plying international waters will clean before they leave their home port or last port of call before arriving into Australia. In-water cleaning of commercial vessels in Australia is only permitted under permit with varying requirements from across the states and territories. This reflects a growing trend to prohibit conventional (uncontained) in-water cleaning (McClay et al. 2015). Applications for in-water cleaning in Australia are currently unlikely to be approved due to the high biosecurity and chemical contamination risks associated with in-water cleaning and treatment. The approval process is complex as it varies among jurisdictions and may involve multiple agencies and port authorities (DAWE 2020). The department is currently consulting on an updated standard which offers a more consistent framework to assess applications for in water cleaning.

A 2018 review of these guidelines recommended that the department develop an in-water cleaning and treatment standard. The department has undertaken projects to identify biosecurity and environmental risks associated with in-water cleaning; these will form the basis of an Australian in-water cleaning and treatment standard. The Baltic and International Maritime Council (BIMCO), through an industry working group, has drafted an industry standard for in-water cleaning with capture (BIMCO 2021), an approval procedure for cleaning companies and explanatory notes. These outline performance-based requirements for in-water cleaning of ships' hull, propeller and niche areas with capture of removed material. The industry standard also includes templates for inspection, service and cleaning reports.



Source: Scianni & Georgiades 2019 (Creative Commons Attribution License, CC BY)

Figure 11: Chemical contamination [C] and biosecurity [B] risks associated with in-water cleaning and waste capture

Australian jurisdictions prefer onshore cleaning because effluent and solids can be captured and disposed at an appropriate facility (EPA SA 2010; DE/MPI 2015). Industry favours in-water cleaning because the cost of in-water cleaning is generally lower than removing a vessel from the water for cleaning (US EPA 2011). However, local water quality and biosecurity concerns linked to in-water cleaning have increasingly become subject to regulation (Tamburri et al. 2020), making in-water cleaning more expensive.

Dry-docking and re-application of coatings reset the clock on biofouling while in-water cleaning moves the hands back. However, the quality of cleaning efforts is important because insufficient removal of biofouling organisms poses a biosecurity risk if leftover organisms are viable. Manual hull cleaning may even enhance the likelihood of subsequent recruitment of fouling organisms by providing chemical and/or physical settlement cues (Floerl et al. 2005), or when the removal of hard calcareous fouling damages the coating. Also, the hull may only be partly cleaned, because of factors such as the size of the vessel, time available, difficult navigation around the vessel, turbid water, lack of light and reluctance of divers to access areas under the hull when a vessel is loading (Rupert Summerson, pers. communication). Ineffective removal of fouling could therefore lessen any relationship between the time since last cleaning and biofouling mass (Ashton et al. 2014). Lane et al. (2018) found that the time since a vessel was last cleaned was a strong predictor for the amount of hull fouling on small vessels (mostly yachts) in Australia. However, results from an in-water survey of non-commercial small vessels in South East Alaska did not detect a significant correlation between the date of last hull cleaning and the extent of biofouling (Ashton et al. 2014). Another survey of recreational vessels, in California, also did not find a significant correlation between time since last cleaning and biofouling cover (Davidson et al. 2010).

In general, in-water cleaning technologies can be divided into two categories: (i) technologies that physically remove biofouling from hull surfaces and (ii) treatment technologies that render biofouling non-viable. Across these two categories there are four approaches that can be used to remove or kill biofouling organisms, namely:

1. manual technologies: hand picking, use of non-powered handheld tools;
2. mechanical technologies: powered tools equipped with brushes, pads, water jets or contactless;
3. surface treatment technologies: heat, acoustic; freshwater immersion; and
4. enclosure technologies: vessel baths, wrapping.

Although these in-water cleaning technologies are listed as reactive measures some of them can also be done proactively to prevent or remove the early stages of biofouling.

Manual technologies involve the removal of biofouling organisms attached to hull surfaces using handheld, non-powered tools. This is often the main method to clean smaller vessels such as recreational yachts and motor launches (Floerl et al. 2010; Inglis et al. 2010). On larger vessels manual cleaning is only undertaken when areas cannot be reached by mechanical equipment. Divers pick macrofouling by hand or remove it using handheld scrapers, brushes, or pads. During manual cleaning of vessel hulls fouling waste is generally not captured but tools are available that, for example, can collect and direct effluent to a reservoir from where it can be disposed at an appropriate facility (Morrisey & Woods 2015).

Mechanical technologies include powered tools that are either designed for handheld use or are part of a semi-autonomous or autonomous cart. Mechanical cleaning of vessels is one of the oldest methods of biofouling control (Yebra et al. 2004). Three different approaches underly currently available mechanical cleaning solutions, namely: (i) brush or pad systems; (ii) high pressure water jets; or (iii) contactless systems (Table 4).

In general, the effectiveness of any type of cleaning or treatment depends on divers visually detecting fouled patches, which requires good underwater visibility. The type of tools used depends on the fouling assemblage and the type of anti-fouling coating (Floerl et al. 2010; Morrisey & Woods 2015).

Table 4: Mechanical cleaning technologies

Approach	Tool	Description	References
Brushes/abrasive pads or blades	Handheld	Use of handheld powered tools fitted with brushes and pads. Removes heavy fouling but not microscopic life-stages. If hard calcareous fouling is removed, these tools can damage the coating. Main method of cleaning for smaller vessels. Some handheld devices can be attached to a pole and be operated by a person above water, but this is unlikely to achieve a full clean. Rotating brushes can effectively remove soft/erect fouling organisms but not all hard-calcareous taxa. Most handheld tools do not capture or filter fouling waste.	Hopkins et al. (2008) Floerl et al. (2010) Inglis et al. (2012) Morrisey & Woods (2015)
	Diver-operated device	Devices with one or more cleaning heads. Larger platforms usually self-propelled. Can be fitted with brushes or pads. Attach to hull surface by suction, waterflow or propeller thrust. Divers can adjust rotating speed to suit the type of biofouling. Rotating brushes can effectively remove soft/erect fouling organisms but not all hard-calcareous taxa. Most systems do not include waste collection and filtration.	Hopkins et al. (2008) Floerl et al. (2010) Lewis (2013) Morrisey & Woods (2015) ACT/MERC (2019) Tamburri et al. (2020)
	Remote controlled	Robots are fitted with rotating brushes and can be tethered or not. Possible elements included: angular sensors, biofilm detectors, compass, video cameras, sonar, depth sensor, global positioning. Robots attach to vessel hulls by magnets, suction, vacuum or thrusters.	Hopkins et al. (2008) Floerl et al. (2010) Morrisey & Woods (2015) USCG (2016) ECOsubsea (2021)

Approach	Tool	Description	References
		Rotating brushes can effectively remove soft/erect fouling organisms but not all hard-calcareous taxa. Most devices are fitted with waste collection and filter systems but the efficacy of these systems may not have been independently verified.	
High pressure and cavitating water jets	Handheld	Divers can influence the direction of the jet. Not for cleaning of large areas of hull. Water blasting can efficiently remove large and microscopically small biofouling organisms from vessel hulls. Cavitating water jets incorporate microscopic bubbles of air and steam, generated by ultrasonic sound. Collapse of bubbles on contact create localised shear stress that removes fouling organisms. Unclear whether cavitating water jets kill fouling organisms. Tools usually do not have collection and filtration systems. Damage to anti-fouling coatings is possible with high pressure and cavitating water jets if applied angle or pressure are not appropriate. Field study found only very little damage to paint. Cleaning using adhesion strength levels should not damage coatings.	Kohli (2007) Floerl et al. (2010) Inglis et al. (2012) Kalumuck et al. (2014) Morrisey & Woods (2015) Oliveira & Granhag (2020)
	Diver-operated device	Some diver-operated systems have adjustable water pressure to optimise the effectiveness of the cleaning. Additional water jets may be used to hold the cart against the hull surface. Water blasting can efficiently remove large and microscopically small biofouling organisms from vessel hulls. Available cart systems include collection and filtration systems and some of the carts fitted with cavitation water jets. Claims that diver-operated cavitating water jet system (Cavi-Jet) is able to remove any level of biofouling, but this may not have been independently verified	Floerl et al. (2010) Inglis et al. (2012) Morrisey & Woods (2015)
	Remote controlled	Robots are fitted with water jets and are usually tethered. Small units for recreational vessels and larger units for commercial vessels. Water blasting can efficiently remove large and microscopically small biofouling organisms from vessel hulls.	Inglis et al. (2012) Morrisey & Woods (2015) USCG (2016)

Approach	Tool	Description	References
		Robots attach to vessel hulls by magnets or turbines. Possible elements included: cameras and depth sensors. Most devices include collection and filtration systems, but the efficacy of these systems may not have been independently verified.	
Contactless	Diver-operated device	Blades create turbulent water flow that generates shear force to dislodge fouling organisms. Designed for FRCs which have minimally adhesive properties. Turbulent water flow can remove fouling if coating is not degraded. Reportedly also works on biocidal anti-fouling coatings without damaging them. Some devices can be equipped with metal ploughs to remove heavy, erect fouling ahead of the brushes. These additional tools are not contactless and may not capture debris. Fitted with collection and filtration systems.	Lewis (2013) Morrisey & Woods (2015) CleanSubSea (2021)

Traditionally, mechanical methods used for larger vessel have been based on the use of brushes to remove biofouling. The material of brushes depends on the type of fouling and the material of the hull. Nylon or propylene brushes are used for slime, algae and soft-bodied organisms, whereas stiffer plastics, steel brushes, or abrasive pads are used to remove hard, calcareous fouling organisms. Nylon or propylene brushes are the preferred option for hulls made of fibreglass, aluminium, steel and wood. Steel brushes are limited to the use on aluminium or steel hulls (Morrisey & Woods 2015). Rotating brush devices are usually effective in removing soft/erect fouling communities but may have limitations in removing assemblages dominated by mature hard-calcareous taxa (Hopkins et al. 2010). Tubeworms have proven to be particular resistant to rotating brush treatments (Hopkins et al. 2008). While being effective, rotating brushes are abrasive and may damage anti-fouling coatings (ACT/MERC 2019), resulting in coating biocides being released into the water during cleaning (Scianni & Georgiades 2019; Tamburri et al. 2020). Dissolved metals, by-products of hull cleaning, may not be captured by filtration only (Lewis 2013; ACT/MERC 2019).

Silicone-based FRCs are soft and not very durable and require their own equipment for cleaning. Stiff rotating brushes may damage the soft topcoats of FRCs and compromise their future performance thus less aggressive brush designs or unit configurations should be chosen for cleaning this type of coating (Holm et al. 2003; Lewis 2009). Townsin & Anderson (2009) indicated that companies offer special cleaning methods for FRCs, taking into account their softer characteristics. However, in-water cleaning undertaken with soft brushes may not remove all biofouling organisms (Lejars et al. 2012). The department’s anti-fouling and in-water cleaning guidelines recommend the use of soft cleaning tools such as cloths, squeegees, and wiping tools for removing all stages of biofouling from FRCs (DE/MPI 2015). A trial of a diver-operated cleaning cart equipped with nylon blades damaged the surface of silicone FRCs due to a jammed plastic jockey wheel and a badly attached cleaning disc. After repair of the unit, cleaning of FRCs was expected to proceed without damage (Lewis 2013). Due to the sensitivity of silicone-based FRCs to reactive cleaning, proactive approaches are more suitable for these coatings.

The development of remotely controlled cleaning robots is a fairly new industry. A recent review of the current market of hull cleaning robots identified 16 robots, but only six of them were commercially available at the time. Seven of the robots were either still undergoing development and testing or used by universities in research projects. The other robots were associated with cancelled projects, out of business companies or their status of development was proprietary information (USCG 2016).

Risk associated with all cleaning methods include unintentional dislodging of fouling organisms by divers operating equipment or by parts of the equipment itself, such as hoses and ropes (Table 3; Hopkins & Forrest 2008; Morrisey & Woods 2015). In-water cleaning activities can miss fouled patches, post-scrubbing surveys showed that cleaning significantly reduced the cover of fouling organisms on the vessel hull but several species across samples persisted (Davidson et al. 2008b). Brush systems with a retaining function can collect a high proportion of defouled material (>90%), 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 & Forrest 2008; Hopkins et al. 2010; Morrisey et al. 2013).

The typical intervals between in-water cleaning interventions may decrease over time as anti-fouling coatings deteriorate and the rate of re-colonisation of hull surfaces with biofouling increases with successive cleaning events (Davidson et al. 2016).

In-water cleaning is an effective method of removing biofilm and biofouling from the hull of a vessel. It mitigates the biosecurity risk of translocating exotic marine species, but it also poses biosecurity and chemical contamination risks if waste is not captured, through releasing biofouling organisms, biocides and dissolved metals into the environment. Proactive in-water cleaning removes the early stages of biofouling to prevent the development of macrofouling and is therefore the preferred approach over reactive in-water cleaning because it poses a lower risk of chemical contamination and the release of viable fouling organisms into the environment. By nature, reactive in-water cleaning is associated with the removal of more complex fouling assemblages, including mature calcareous fouling organisms. More aggressive cleaning methods are more likely to release higher concentrations of chemical contaminants into the environment, and together with the presence of more mature biofouling organisms, reactive in-water cleaning poses a higher relative risk to biosecurity and water quality (Lewis 2020).

Surface treatment technologies are an alternative to abrasive cleaning technologies for vessel hulls. They include heat and acoustic treatments.

Heat treatment involves the application of heat with the intention to render biofouling organisms non-viable. Dead soft-bodied organisms will detach eventually while cemented taxa will likely remain attached unless they are removed by some means (Inglis et al. 2012). Non-removal of fouling means that the vessel will most likely not improve its operational performance or fuel consumption following heat treatment (Inglis et al. 2012) and be re-fouled because the anti-fouling or foul-release coating would have been compromised by surface fouling, which leaves behind biogenic cues for settlement if the surface is not chemically sterilised (Floerl et al. 2005b).

The intended outcome of all heat treatments is the same but how the necessary heat is generated and how it is applied varies among the treatments. Fouling species are killed *in situ*, so heat treatment does not require collection and filtration of fouling waste, but it is important that the assumption of non-viability is verified. Seemingly successful treatments can turn out to be not effective, as was the case for a heavily fouled tug that was treated under water with low pressure hot water by divers in New Zealand (Morrisey & Woods 2015).

Wotton et al. (2004) used sealed plywood boxes attached to a sunken trawler to eradicate an invasive seaweed, *U. pinnatifida,* with heat treatment. The boxes were held against the hull with magnets and the water inside the boxes was heated to a target temperature of 70 degrees Celsius. Heating elements were powered by a diesel generator. The boxes remained in one spot for 10 minutes. A flame torch was used to treat the areas of the hull where the boxes could not be attached properly due to bent or curved plating. The heat treatment was successful in killing all viable sporophytes of the invasive seaweed as confirmed by several post-treatment dive surveys (Wotton et al. 2004).

Fouling species have different heat tolerances that should be considered when applying heat treatment methods to attached fouling organisms or suspended in effluent water. Some species may be able to insulate themselves from heat, in particular those taxa with calcareous shells or tubes (Morrisey & Woods 2015). In an example, the effectiveness of heat treatment of marine mussels depended on mussel size and temperature (Rajagopal et al. 2005a). Bigger mussels could withstand heat treatment for longer than smaller sized mussels. Small mussels reached total mortality at 36 degrees Celsius after 84 minutes but were all killed after 1 minute when exposed to 40 degrees Celsius. Heat treatment for surfaces covered by mussels is recommended to be applied during breeding periods, when settling mussels are small and adults weakened by spawning (Rajagopal et al. 2005a). In comparison, invasive oysters tolerated increased temperatures for longer. In another experiment, similar sized Pacific oysters were killed after being exposed to 39 degrees Celsius for 163 minutes. Size of the tested organisms influenced mortality with the largest sized oysters reaching 100% mortality after 167 minutes at 40 degrees Celsius (Rajagopal et al. 2005b).

Heat treatment of vessel hulls is not a routine management option and its efficacy, especially for the treatment of complex biofouling assemblages, has not been evaluated independently (Inglis et al. 2012; Oliveira & Granhag 2016). Moreover, there does not seem to be a prototype treatment system for hulls of recreational vessels. One reason for this could be that heat treatment is not considered a viable option for use on recreational vessels because of the unknown but potentially bad effects of heat on the integrity of fibreglass and epoxy surfaces (Inglis et al. 2012).

Acoustic treatments are another non-toxic alternative for removal or biofouling prevention. In general, acoustic systems for the treatment of biofouling consist of a signal generator, a power amplifier and a transducer that causes vibrations to the hull surface. Acoustic signal can be emitted in the ultrasonic (>20 kHz) and audible (20 Hz-20 kHz) frequency range (Legg et al. 2015).

Ultrasonic treatment is frequently used in surface treatment industries, but it also has had some successful outcomes reported in the literature in the context of biofouling. Some studies found that ultrasonic protection systems prevented settlement of fouling species while others found that ultrasonic treatment removed them (Legg et al. 2015).

For example, a recent field study used test plates coated partly with anti-fouling coatings, equipped them with an ultrasonic system and submersed them into seawater in a sheltered port environment. Ultrasonic power levels emitted were low with a frequency output of 47 kHz. Compared to a fouled control, the test plates showed no signs of biofouling after 34 days. The ultrasonic system effectively prevented biofouling in the field study by causing a repelling mechanism that controls biofouling without adverse effects to marine life (Habibi et al. 2016). In contrast to this study, an investigation of the efficacy of an ultrasonic system installed on a vessel found that the area that should have been protected by the system was covered with a thick and complex fouling assemblage (Lewis 2016).

The use of acoustic signals emitted in the ultrasonic frequency range can also remove biofouling from surfaces. Laboratory tests and a cleaning test on a real vessel hull showed that ultrasound was able to clean hull surfaces covered with biofilm (Mazue et al. 2011). For the method to be effective two factors were most important, namely the distance between the ultrasound emitting surface and the vessel hull, and the appropriate operating speed of the transducer. Guo et al. (2011) found that ultrasonic treatment reduced settlement of barnacle cyprids (secondary stage macrofouling) and killed some of them when they were exposed to signals with frequencies ranging from 23 to 102 kHz. Lower frequencies induced lethal effects while higher ultrasonic irradiation reduced settlement of cyprids on test vials. Kitamura et al. (1995) also found that lower ultrasonic frequencies, of 19.5 kHz, killed barnacle cyprids. In later laboratory work, Guo et al. (2013) confirmed that collapsing ultrasonic cavitation bubbles can generate pressures that induce injuries such as broken shells on juvenile barnacles leading to their death. Newly attached barnacles could be removed, making ultrasound cavitation optimal when applied to the early stages of fouling, before hard calcareous structures are formed.

The use of acoustic signals in the *audible range* resulted in less successful study outcomes in terms of its effect on biofouling. Study results are inconclusive, some studies reported settlement inhibition but others found no effect when compared to controls (Legg et al. 2015). Some studies have even found a potential biofouling growth enhancing effect of vessel noise. Noise from vessel hulls may attract larvae and enhance their survival and growth as larvae were found to settle faster when they were exposed to underwater noise. More than twice as many bryozoans, oysters, calcareous tube worms and barnacles settled and established on experimental panels treated with vessel noise compared to controls (McDonald et al. 2014; Stanley et al. 2014).

Currently, the use of acoustic energy has limited applicability in controlling of biofouling and the installation of ultrasonic treatment systems is expensive (Grandison et al. 2011). Legg et al. (2015) noted that further research is required to optimise operating parameters and practical circumstances of acoustic anti-fouling systems that are able to target a wide range of fouling organisms. This would require a standard methodology, more photographic documentation and the inclusion of controls to study negative consequences on marine life (Legg et al. 2015). Further research should also consider the effects of acoustic treatments on coating integrity and the capture of removed fouling organisms and fragments.

Freshwater immersion is another treatment that intends to kill marine fouling organisms *in situ* by osmotic shock without removing them. Vessels can navigate into a freshwater river environment or into a purpose-built freshwater lock (Inglis et al. 2012).

Three field-based studies report on the outcomes of freshwater treatment of obsolete, heavily fouled vessels. One obsolete vessel was a decommissioned US navy battleship, the *USS Missouri*, that had 76 fouling species identified on its hull (Brock et al. 1999). On its way to Hawai'i from Oregon the vessel made a detour and was immersed in near fresh water of the Columbia River for nine days (Apte et al. 2000). After the low salinity treatment it continued its transoceanic crossing to Hawai'i in warmer water temperatures. At the end of the journey more than 90% of the hull was clean of any biofouling and only 11 species were found alive, some of which died in the days after arrival (Brock et al. 1999). In this case immersion in low salinity water was an effective method to reduce, but not eliminate, temperate fouling communities on a vessel hull. Elimination of biofouling was not successful possibly because the deepest part of the vessel hull was exposed to brackish water instead of freshwater. Evidence for treatment failure were settled mussels found on a different vessel in the destination port that could be traced back to the towed navy vessel because people observed spawning activity two hours after the arrival of the *USS Missouri* (Apte et al. 2000). Treating the *USS Missouri* in near fresh water was about ten times less expensive than dry-docking and cleaning the obsolete battleship (Brock et al. 1999).

The other field study did not find a strong effect of freshwater exposure on biofouling, possibly due to low vessel speeds which can enable retention of initial fouling communities (Davidson et al. 2012). A decommissioned oil tanker and a sea transportation service vessel were towed from California to Texas, via the Panama Canal. Pre-transit surveys identified 22 species of macroinvertebrates on the vessel hulls. The voyage was characterised by high temperature and salinity variations. Both vessels spent about 7 days in a freshwater environment when they were transiting through the Panama Canal. At the end of the voyage post-transit surveys showed that biofouling extent had decreased but also revealed an unexpected increase in species richness which indicated that new species had settled on the vessels during their slow voyage. Sea chests were not a source of additional biota in this study. Although reduced in biomass, some bryozoan and barnacle species from the pre-transit surveys were detected in 98% of the samples collected post-transit, persisting through changes in environmental conditions (Davidson et al. 2012).

Three experimental studies investigated the efficacy of freshwater treatment on marine species under controlled laboratory conditions. A study in New Zealand exposed the seaweed pest *Undaria pinnatifida* to freshwater immersion at 10 and 20 degrees Celsius. Total mortality of seaweed gametophytes at 10 degrees Celsius was achieved after two days and >80% of gametophytes were already dead after one day. At 20 degrees Celsius, all gametophytes died within a day with >90% mortality achieved after only twelve hours (Forrest & Blakemore 2006). In Alaska, an aquarium-scale experiment tested the effects of freshwater treatment on the invasive colonial ascidian *Didemnum vexillum*. Freshwater immersions for four hours achieved complete colony mortality in this experiment (McCann et al. 2013). Moreira et al. (2014) exposed two invasive pest corals to a freshwater treatment in Brazil. Coral species were attached to ceramic tiles fixed onto concrete blocks. Exposure to freshwater killed both coral species after a period of two hours. The results from these laboratory experiments indicate that freshwater could be combined with encapsulation as a non-toxic method to kill biofouling organisms on vessel hulls.

Freshwater treatment is unlikely to be a feasible option for international vessels (commercial and recreational) arriving in Australia, because rivers may not be near main ports of entry or accessible for large or keeled vessels. Treating a vessel's hull with this method requires large volumes of freshwater and exposure to freshwater may stimulate spawning in some organisms when they are under osmotic stress (Inglis et al. 2012).

Encapsulation technologies are an emerging biofouling treatment option but their use is not widespread (Roche et al. 2015; Ammon et al. 2019). Encapsulation technologies intend to isolate and kill fouling organisms by enclosing vessel hulls in an impermeable membrane that reduces water exchange and deprives organisms within the enclosed area of oxygen, food and light. Encapsulation does not remove biofouling, so dead organisms are left *in situ* (Inglis et al. 2012).

Technologies applying this principle include vessel baths and wrapping. *Vessel baths* are intended for ongoing hull maintenance but due to their flexible deployment they can also be used for incursion response treatments. *Vessel baths* consist of a floating collar with a plastic membrane suspended from it to form an enclosed, water-filled compartment. Vessels can enter through the back end of the dock. Water can then be pumped out as much as needed. These type of enclosure systems are mobile and flexible and can accommodate different sized and shaped vessels (Morrisey & Woods 2015). Some vessel baths are installed permanently at marina berths (Floerl et al. 2010).

A Tasmanian company has developed a special version of a vessel bath, the IMProtector™, initially designed for recreational yachts. This system is a reusable shroud that can be deployed around vessels of up to 18m in length without the help of divers. Prototypes of this system are currently being deployed around Australia and overseas and can treat small vessels such as yachts but also large commercial ships, dredges and marine infrastructure (BFS 2020). However, the volumes of water needed for treatment of large vessels would require large pumping systems, affecting the feasibility of this approach for commercial vessels (Inglis et al. 2012).

Encapsulation technologies offer two options for killing biofouling organisms. The first option is to enclose a vessel and 'set-and-forget' about it, allowing the water in the compartment to become anoxic. Preliminary research indicated that mobile fauna was killed within 24 hours and all taxa died between four and nine days after enclosure commenced (Floerl et al. 2010). This method is not suitable for vessels with short port visiting times (Hopkins & Forrest 2008; Inglis et al. 2012). The other option is to increase the effectiveness of the enclosure treatment, by adding biocides to the residual water around the vessel hull. The most common addition in New Zealand is granulated chlorine which reportedly is effective, but some more resilient taxa, such as bivalves may be able to persist. The suitable encapsulation time depends on the level and type of biofouling, and local conditions (Aquenal 2009c; Ammon et al. 2019).

A recreational yacht was encapsulated in a floating dock in New Zealand and chlorine added to the enclosed compartment to treat an infestation of the invasive polychaete *Sabella spallanzanii* (Morrisey et al. 2016). Exposure to the biocide lasted for 17 hours before residual chlorine was neutralised. Immediately after chlorine neutralisation most investigated polychaetes were dead with visible lesions and damages. A survey six days after the treatment confirmed that encapsulation combined with biocide addition had eliminated all biofouling organisms on the hull, including oysters and macroalgae (Morrisey et al. 2016).

In the UK, researchers developed a novel encapsulation system or 'decontamination berth' for recreational vessels as a tool for responding to the risk of spread of the invasive colonial ascidian *Didemnum vexillum* (Roche et al. 2015). This system can enclose vessel of up to 10 m in length and uses material commonly used in rigid-inflatable boats. The novel aspect of the berth is an integrated pumping system. Once a vessel has entered the berth at the back, the surrounding seawater can be pumped out and replaced with a chemical solution which is held in a separate storage bag if not in use. At the end of the treatment the chemical solution can be pumped back into the storage bag and seawater returned to the compartment. Field trials using the system in conjunction with sodium hypochlorite confirmed the effectiveness of this treatment. Based on experimental results recreational vessels infested with *D. vexillum* are recommended to be exposed to the treatment chemical for 15 minutes (Roche et al. 2015). Roche et al. (2015) did not provide details about where the surrounding seawater is pumped to, which is an important gap in the description of this encapsulation system. Also, any encapsulation method bears the risk of biofouling organisms being accidentally dislodged from the vessel when deploying the encapsulation system (Inglis et al. 2012).

Wrapping involves enclosing vessel hulls or other marine structures with strips of material, rather than fully enclosing them in a single bag. Overlapping margins are sealed with adhesive tape. Wrapping generally uses less robust material than floating docks and shrouds and is thus more suitable as a rapid response tool for treating existing fouling (Morrisey & Woods 2015). Some researchers and practitioners consider wrapping to be a promising tool for treating vessels *in situ*, but there is currently no standardised approach including recommendations for application in the field (Keanly & Robinson 2020). However, available field studies can give some indication for the required treatment duration.

A wrapping approach was used for treatment of 27 vessels *in situ* in New Zealand ranging in size from 7 to 30 m. The aim was to eradicate the invasive colonial ascidian *D. vexillum*. All vessels were enclosed by using custom shaped plastic silage covers and acetic acid was added. The treatment lasted for seven days and the method achieved total mortality of the targeted invasive species. Dropped biofouling material was released into the surrounding marine environment. Higher concentrations of the acid could be used to ensure the same effectiveness at shorter treatment duration (Pannell & Coutts 2007; Floerl et al. 2010). A similar approach was used to treat two infected, structurally unsound barges which needed to be treated *in situ* to eradicate the same invasive colonial ascidian. The vessel hulls were wrapped with polyethylene sheets and chlorine granules added. Again, wrapping and addition of a biocide achieved eradication (Coutts & Forrest 2007).

A field experiment conducted in a New Zealand marina used fouling assemblages consisting of soft and hard-fouling species to test the efficacy of a wrapping treatment. Fouling species attached to settlement plates were fixed onto experimental blocks and wrapped with clear PVC pallet wrapping and underwater PVC tape. Some test units were also treated with acetic acid or kept at warmer temperatures. Soft-bodied fouling organisms required treatment times of 1 to 3 days. Most mussels and bryozoans, the most resistant taxa, were dead after 10 days when encapsulated without acetic acid. Total mortality of all individual test species was achieved after 15 days. Adding acetic acid to the encapsulated units significantly reduced the time required to achieve total mortality to 48 hours. Temperature also strongly influenced mortality; the likelihood of death was up to eight times higher at 19 degrees Celsius than at 10 degrees Celsius (Atalah et al. 2016).

Keanly & Robinson (2020) encapsulated four recreational yachts using an unspecified encapsulation device in a field experiment in South Africa. Study results showed that the encapsulation treatment was effective in eliminating all biofouling species. After five days all existing biofouling organisms on the vessel hulls were eliminated. Similar to Atalah et al. (2016), the study also found that the tested soft-bodied ascidian was more sensitive to encapsulation than the tested invasive mussel. Differences in treatment duration until total mortality of all mussels was achieved between the two studies might have been due to smaller sized mussels and a warmer test environment in the South African study.

Mantelatto et al. (2015) used two different types of wrapping material in an encapsulating experiment involving two invasive coral species. One experimental wrap consisted of polyethylene sheets and the other of woven polyethylene plastic (raffia). The invasive coral species were collected from an Island in Brazil and were transplanted to the experimental site. After seven days of wrapping all polyps of the two coral species were dead. While the plastic sheets were more efficient in killing the corals the raffia material was easier to manipulate underwater, cheaper and more durable. The authors considered the wrapping method suitable for use on marine vessels.

Encapsulation technologies are established and effective tools for marine biosecurity interventions, but they they can be unwieldy and inconvenient to use as an in-water treatment for biofouling. For small vessels, haul out and cleaning is cheaper than deploying in-water enclosure systems (Ammon et al. 2019). Encapsulation systems and wrapping are not feasible for owners of the majority of international commercial and recreational vessels because of the time it takes for the treatment to take effect. The time that vessels are required to remain immobile makes these methods not feasible for large commercial vessels, because they mostly have port turnaround times of <4 days and encapsulation or wrapping would cause significant delays to the vessel schedule and additional costs (Inglis et al. 2012; Growcott et al. 2016). Wrapping material can tear and potentially leak exotic biofouling organisms into the environment (Inglis et al. 2012).

6.3.2.2 Niche areas

Niche areas are areas on vessels that are protected from hydrodynamic drag forces. They are often not covered by anti-fouling coatings because most niche areas are difficult to prepare and coat even when the vessel is in dry-dock (Bohlander 2009). Some areas are not suitable for coatings altogether, such as sacrificial anodes. The cleaning of niche areas is often not a priority for vessel owners as they are more concerned with the efficiency related impacts of biofouling on hull surfaces, with the exception of propellers and DDSS. 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).

The position, size, and design of niche areas determines the complexity and scale of the cleaning system that will be used. Vessels vary in their structural characteristics and have different numbers and designs of niche areas that may need customised cleaning solutions (Growcott et al. 2019).

Some niche areas are not easily accessible for underwater mechanical cleaning with remote controlled robots, diver-operated carts, or other large equipment designed for hull cleaning. These areas often require manual cleaning or mechanical cleaning by hand-held devices such as scrapers, hand-held rotary brushes and water blast wands (McClay et al. 2015; Morrisey & Woods 2015). As the size, number and complexity of sea chests increases with vessel size (Coutts & Dodgshun 2007), the internal pipework of larger vessels can also be expected to provide more colonising opportunities for fouling species. Internal seawater systems are a vessel's internal pipework and associated components such as valves, pumps, strainers and joints (Bracken et al. 2016). Biofouling communities in internal seawater systems may go undetected if a vessel has a clean hull (Neil & Stafford 2005; Cahill et al. 2019b). In general, recreational vessels are expected to contain mostly low levels of biofouling because they use small diameter pipework with multiple bends, valves and manifolds (Cahill et al. 2019b).

Reactive measures for external and internal niche areas will be discussed in the following order:

External niche areas

1. propeller polishing;
2. manual cleaning;
3. rotating brushes;
4. pressurised water;

External and internal niche areas

5. encapsulation;

Internal niche areas

6. thermal treatment;
7. freshwater treatment;
8. chemical treatment with oxidising biocides;
9. chemical treatment with non-oxidising biocides; and
10. non-biocidal treatments.

6.3.2.2.1 Propeller polishing

Apart from hull fouling, biofouling and corrosion of propeller blades also contribute to a reduction in operational performance as the surface roughens (Zhang et al. 2016). Maintaining a clean hull and propeller are important for fuel efficiency of commercial vessels (Buhaug et al. 2009; Townsin & Anderson 2009; Farkas et al. 2021). Current propeller maintenance practices recommend polishing propellers in intervals of 6-12 months to remove slime from blade surfaces, before hard calcareous layers build up (Hydrex 2012; Georgiades et al. 2018). Propeller polishing is a basic, low-cost strategy undertaken between dry-dockings to regain losses in performance. Propeller polishing at six-month intervals was estimated to result in fuel savings of five tons per day for containerships travelling at speeds of 24 knots (Munk et al. 2009). In other terms, the decrease in fuel consumption by polishing a roughened propeller surface was estimated to be in the order of 1 – 3% (Wilkinson 1988; Witmer & Whiteside 1988; Buhaug et al. 2009).

Propeller polishing is conducted by using hand-held devices that can be fitted with different types of brushes (e.g. silicone, polypropylene, nylon, or steel), cutter blades or abrasive pads (Morrisey & Woods 2015). Small units of diver-operated rotating brush systems are able to clean slightly curved surfaces such as propeller blades (Floerl et al. 2010). Some cleaning devices have been designed specifically for propeller polishing and can be fitted with barnacle cutter attachments for heavy biofouling (Armada Systems 2020). Propellers can also be polished using Cavi-Jet/grinding technology which combines grinding and cleaning with cavitating water into a single cleaning unit (Limpieza Purotecnica 2020). Townsin & Anderson (2009) recommended grinding and polishing propeller blade surfaces little but often. As most hand-held cleaning devices do not include capture and filtration systems for waste (Morrisey & Woods 2015), propeller polishing poses a biosecurity risk.

Atlar et al. (2002) stated that a loss in propeller efficiency could be avoided by applying FRCs on propeller blades as it would give a surface finish equivalent to that of a new or well-polished propeller. How long that effect would last is unclear (Townsin & Anderson 2009). Traditionally, propellers are not coated, at least partly, as turbulent water and cavitation quickly erode the coating system. However, as forecasted by Atlar et al. (2012), silicone FRCs have recently been used in combination with high performance anti-corrosive coatings to protect propeller blades from biofouling and reduce the need for frequent propeller polishing (Lewis 2020). For example, Oceanmax (Propspeed) and Greencorp Marine (PropOne) have developed FRCs to prevent biofouling on propeller blades and other underwater metallic running gear. Results from tests at model scale indicated that propeller blades coated with FRCs did not reduce propeller performance (Korkut & Atlar 2012). Abrasive cleaning methods are not recommended, if FRCs have been applied to propellers.

6.3.2.2.2 Manual cleaning

Hand-operated non-powered tools for manual cleaning include cloths, brushes and plastic or metal scrapers. The scraping of biofouling by hand is time-consuming and thus not suitable for cleaning of large areas but suitable for cleaning of external niche areas and edges (Inglis et al. 2012). It cannot treat internal niche areas such as sea chests and internal pipework. In general, harder scrapers are used for heavier fouling and on hard anti-fouling coatings. Scraping is the most common method of in-water cleaning for recreational vessels. Biological waste is usually not captured but some handheld scrapers are equipped with collection and filtration systems that use vacuum and direct the effluent to a sewage truck that can dispose of the waste at an appropriate facility (Morrisey et al. 2013; Morrisey & Woods 2015), however their capture efficiency is likely to be dependant on the skill of the operator. One product uses high frequency oscillations of the blade to remove barnacles and other biofouling organisms without applying pressure and without damaging underlying coatings. It can be fitted with a special guarded blade for cleaning of silicone FRCs and accessories for cleaning of shafts, anodes, trim tabs, keel coolers and other small structures (Waveblade 2020). Hand scrapers can damage anti-fouling coatings, resulting in corrosion and fouling (Bohlander 2009).

The use of scrapers, releases fouling organisms into the marine environment, if waste is not captured, often in a viable condition. A high proportion of soft-bodied taxa can be released undamaged in comparison to hard-bodied taxa (Woods et al. 2007). Cleaning of vessels that are encapsulated in a vessel bath or shroud makes manual cleaning less of a biosecurity concern as all biological waste is captured in the enclosed water compartment. However, manual cleaning in tight spaces is associated with occupational health and safety concerns (Morrisey & Woods 2015).

In-water manual cleaning is unlikely to be applied to international recreational vessels arriving in Australia, because it is easier to haul smaller vessels out (Georgiades et al. 2020).

6.3.2.2.3 Rotating brushes

Handheld cleaning systems with rotating brushes, and a fitted capture system, can retain most of the material removed from the hull but capture rates decrease with the level of biofouling on curved surfaces (Hopkins & Forrest 2010; Morrisey et al. 2013). As most handheld tools do not capture or filter cleaning waste, this method bears biosecurity and chemical contamination risks (Morrisey & Woods 2015). The majority of the fouling organisms that are not retained by capture systems get crushed by rotating brushes and are not viable (Hopkins et al. 2010), but this also depends on the level and type of fouling, the type of brush system, and the skill of the operator. Brush systems may not reach the fouling in external niche areas. Hopkins et al. (2010) tested two diver-operated rotating brush systems for cleaning of niche areas and concluded that the tested systems were not suitable for cleaning sea chests, anode straps and gratings and would need to be complemented with other methods. As most in-water cleaning devices are not designed to clean curved or hard to reach areas, these areas often remain untreated between dry-dockings (Hopkins & Forrest 2008).

If anti-fouling coatings are applied to niche areas that are accessible to mechanical cleaning, they might be damaged by using abrasive brush-based cleaning systems (Floerl et al. 2010; Morrisey & Woods 2015). However, brush systems can also rejuvenate some coating types and improve their performance (DE/MPI 2015).

Bohlander (2009) noted that the underside of the bilge keel is usually easy to clean using single brush units operated by divers. The inside of sea chest intakes and discharges is difficult or impossible to reach. Divers can try to remove sea chest gratings for better cleaning access, but attempts may be hampered by corroded bolts or designs that do not permit grate removal. Other niche areas that are difficult to reach include the areas above the rudder and thruster tunnels.

6.3.2.2.4 Pressurised water

Diver-operated wands that discharge pressurised water or cavitating water jets may be able to reach some of the more complex external niche areas but these tools can also damage any applied anti-fouling coatings in these areas if water flow is too high (Bohlander 2009) or the angle of the water flow directed to the fouled surface too steep (Floerl et al. 2010; Morrisey & Woods 2015). Water blast systems are versatile in that divers can adjust operating pressure and jet pattern according to coating type and extent of biofouling (DE/MPI 2015). High pressure water jetting is considered to be a faster cleaning method than scraping and brushing (Inglis et al. 2012), but most systems do not capture cleaning waste which poses a biosecurity and chemical contamination risk (Inglis et al. 2012).

The company that developed Cavi-Jet equipment for cleaning of fouled surfaces using cavitating water offers single-sprayer pistol shaped devices for cleaning of hard to access niche areas such as rudder and propeller shafts and thruster tunnels (Floerl et al. 2010; Limpieza Purotecnica 2020).

Lewis (2013) conducted in-water cleaning trials of niche areas using a 'magic box', a transparent plastic box that can be attached onto an anode or other hull appendage by suction. The box is connected to a trash pump and provides access ports for high pressure water wands. This system was effective in removing and capturing all visible fouling from on and around the anode. The high pressure water wands removed the fouling organisms and the 'magic box' captured them for extraction through a suction hose connected to the trash pump.

6.3.2.2.5 Encapsulation

Encapsulation was covered as an alternative treatment for killing biofouling organisms on vessel hulls in section 6.3.2.1.3 and will only be discussed here in particular reference to niche areas.

Some authors believe that encapsulation methods can be used to effectively treat biofouling of external and internal niche areas. For example, Roche et al. (2015) deemed encapsulation approaches effective as well because it allows any added chemicals to penetrate into the niche areas of vessels. Growcott et al. (2016) also found encapsulation to be suitable for treating sea chests and internal pipework and pointed out that this method can be applied to niche areas of any sized vessel with the benefit that fouling waste is contained in the enclosed compartment. If chemicals are added to the enclosed water to achieve complete mortality of biofouling organisms, practitioners need to ensure an even distribution of the dissolved chemical throughout the niche areas which is difficult to achieve.

Inglis et al. (2012) stated that encapsulation is suitable for treating niche areas such as through-hull fittings, saltwater systems (e.g. toilets and cooling systems) and areas around propellers and rudders without mechanical disassembly. However, the authors also highlighted that it would be a serious inconvenience for recreational vessel owners and cruise passengers to be required to anchor for the time it takes for the encapsulation treatment to take effect. The time that vessels are required to remain immobile makes this method also not feasible for large commercial vessels, even if encapsulation systems exist, because of significant delays to the schedule of vessels with turnaround times of <4 days and the associated costs (Inglis et al. 2012; Growcott et al. 2016).

There is uncertainty about the extent to which encapsulation treatments are effective in treating all fouling organisms from vessel hulls. Sea chests and pipework may provide protection for organisms from the effects of encapsulation. Cahill et al. (2019b) argued that many pipework systems frequently experience conditions of low oxygen concentration when not in use and may therefore house fouling organisms that have adapted to these conditions and can tolerate low/zero oxygen conditions. The effectiveness of encapsulation systems is likely to vary, depending on the diversity of fouling taxa, extent of biofouling, hull type and treatment conditions.

The outcomes of encapsulation treatments are not surveyed and recorded routinely but practitioners who have to manage the risk of introduction of exotic marine species via vessel biofouling would benefit greatly from such information (Ammon et al. 2019).

6.3.2.2.6 Thermal treatment

The treatment of vessel hulls with heat has been described in section 6.3.2.1.3. This section will discuss the application of thermal treatment to internal niche areas such as sea chests.

Piola & Hopkins (2012) investigated the efficacy of heated seawater for the treatment of fouled sea chests. They determined appropriate temperature regimes for common fouling taxa in laboratory trials prior to conducting field trials using a replica sea chest environment. All taxa tested in the laboratory heat treatment experiments showed 100% mortality when exposed to 42.5 degrees Celsius for 20 minutes. The most heat tolerant species were the barnacle *Elminius modestus* and the oyster *Magallana gigas* which recorded survival rates of 100% in 37.5 degrees Celsius for 60 min and 64% in 40 degrees Celsius for 30 min (complete mortality of adult oysters was achieved following exposure to 57.5 degrees Celsius for 60 minutes, or 60 degrees Celsius for 30 min). The same temperature regimes were then applied to the replica sea chest. The seawater in the chest was heated to the target temperatures but could not be distributed evenly within it. There was a gradient in the chest with water reaching the target temperature at the top where the inlet was and cooler water at the bottom of the chest. This water temperature gradient was reflected in the treatment outcomes. Fouling taxa had higher mortality rates at the top and middle of the sea chest than at the bottom (Piola & Hopkins 2012). Growcott et al. (2017) have suggested a treatment threshold of 60 ± 2 degrees Celsius for 60 min for reactive treatment purposes.

Leach (2011) tested the use of heated seawater to treat biofouling in sea chests using a similar approach. He also did a laboratory immersion experiment first to determine the appropriate temperatures and times for achieving total mortality of fouling species. A subsequent field study involved the development and use of a replica sea chest. The most common fouling taxa on the settlement plates were bryozoans, aquatic invertebrate animals, and polychaete worms. In the laboratory experiment all fouling taxa were dead after exposure to 40 degrees Celsius for 15 min. In the field study the replica sea chests were submerged in seawater and the HST technology attached to heat the water inside the chest. Treatment results showed that immersion at 40 degrees Celsius for 15 min killed secondary fouling organisms but temperatures of 60 degrees Celsius for 10 min were needed to eliminate tertiary fouling organisms. Like Piola & Hopkins (2012), Leach (2011) also observed temperature variability within the replica sea chests.

These study results indicate that heated seawater, in general, is an effective and environmentally safe approach for treating biofouling in niche areas, however, practical application on vessel sea chests remains a challenge (Piola & Hopkins 2012) because dead fouling organisms are not captured and the efficacy of this treatment to treat structurally complex biofouling assemblages is unknown (Inglis et al. 2012). Customised heat treatment systems need to undergo testing and further research should investigate the effects of heat treatments on mobile organisms (Growcott et al. 2019) and anti-fouling coatings (Inglis et al. 2012).

6.3.2.2.7 Freshwater treatment

Immersion of fouling organisms in freshwater can be used as a treatment of biofouling assemblages in protected internal niche areas. Freshwater exposure kills fouling organisms by osmotic shock *in situ*. The use of freshwater for treatment of hull fouling and freshwater tolerance of different fouling taxa was described in section 6.3.2.1.3. In this section the focus will be on the efficacy of freshwater treatment for internal niche areas.

A recent experiment on the effectiveness of freshwater immersion for eliminating fouling species used settlement panels with two years' worth of mature biofouling assemblages (which included only few calcareous biofouling organisms and no mussels, barnacles or oysters) and exposed them to different salinity treatments in a model sea chest. The sea chest was flushed with seawater of different salinity levels. The 2-hour salinity 7 ppt (the lowest salinity) treatment killed all of the macrobenthos on the panels one week after the treatment, except for one native colonial tunicate species. Biofouling on panels exposed to salinity 20 ppt and 33 ppt was largely unaffected (de Castro et al. 2018).

Immersing a vessel in freshwater allows the freshwater to reach all the niche areas on the vessel, including internal seawater systems and exposes any biofouling organisms in these areas to low salinity or zero salinity conditions (Bell et al. 2011). However, adequate mixing is required to achieve the desired salinity for an appropriate period of time. Immersion in freshwater requires access to navigable rivers near first port of entries. Because these are not very common, and due to costly delays to vessel schedules and the risk of propagule release, this treatment is unlikely to be feasible for international recreational and commercial vessels (Inglis et al. 2012; Growcott et al. 2016).

6.3.2.2.8 Chemical treatment with oxidising biocides

As MGPS cannot prevent biofouling with absolute certainty and their efficacy has been questioned (Grandison et al. 2011; Frey et al. 2014; Growcott et al. 2016; Lewis 2016), remediation strategies are required to mitigate the fouling pressure on affected areas of the internal seawater system. Which remediation techniques are chosen depends on the level and location of the fouling. A common remediation technique is chemical treatment using oxidising biocides. Oxidising biocides irreversibly damage (by chemically oxidising) the cellular integrity of the organism, causing death (Grandison et al. 2011). Below is a list of oxidising biocides used for the treatment and disinfection of water and vessel infrastructure, some are available commercially while others are used experimentally (Growcott et al. 2016). Refer to Jenner et al. (1998) Venkatesan & Murthy (2009), Grandison et al. (2011), Bracken et al. (2016), Growcott et al. (2016, 2017) and Cahill et al. (2019b) and references therein for more information on these biocides.

- **hydrogen peroxide***: degrades rapidly which makes it environmentally friendly, but it may not be effective in convoluted pipe networks.
- **iodine**: its efficacy for reducing biofouling in seawater piping systems is unclear; it is commonly used in the food and medical industries, can produce toxic by-products.
- **chlorine dioxide***: is effective over a greater range of water conditions and more effective for control of fouling organisms than sodium hypochlorite for example; effective in killing

macrofouling and microbes; low corrosion rate of pipes; cannot be generated from seawater, expensive relative to chlorine.

- **ferrate ion***: is a stronger oxidant than bromine or chlorine and can be used without harmful by-products but it requires onboard chemicals and the technology has not been tested on adult biofouling organisms in internal seawater systems.
- **peracetic acid***: degrades rapidly but may be less effective in controlling biofouling than sodium hypochlorite or chlorine dioxide; is corrosive and unstable; more expensive than chlorine dosing; potential environmental risks associated with discharge.
- **bromine***: is similarly effective to chlorine in controlling biofouling but more stable; performs better at high pH but less effective in acidic environments; much more expensive than chlorine; efficacy of bromine can be increased when used in conjunction with other treatments (e.g. chlorination).
- **ozone**: may not be more effective than chlorine in treating biofouling; reacts with bromide in seawater; difficult to maintain effective dosing regime because ozone breaks down very rapidly; is influenced by seawater chemistry; is corrosive and has high installation and operation costs.
- **descalers (e.g. Rydlyme)**: chemically degrade the calcareous shells and casings of biofouling organisms achieving high mortality rates; different formulations with varying effectiveness; may corrode internal pipework; do not completely dissolve organic material; potential environmental risks associated with discharge.

*These oxidising biocides are in development for use in treatment of internal seawater systems (Growcott et al. 2016).

6.3.2.2.9 Chemical treatment with non-oxidising biocides

Non-oxidising biocides interfere with cellular transport mechanisms or disintegrate cellular protein structures. At first, targeted fouling organisms do not detect organic agents they are exposed to as toxic. Only when they experience the first detrimental effects do they change behaviour (Jenner et al. 1998). As non-oxidising biocides affect specific metabolic processes a single chemical is insufficient in treating a broad spectrum of fouling organisms. Non-oxidising biocides are highly effective but require long contact times and are used at high dosages which can make them an expensive solution if unit costs are high. Most of these biocides do not corrode internal seawater systems (Grandison et al. 2011).

Commonly used non-oxidising biocides for treatment of internal seawater systems are quaternary ammonium compounds (QAC) but many compounds that are successfully being used overseas to treat biofouling are not registered for use in Australia or have limited use permits. Microbial organisms developing resistance to non-oxidising biocides is an issue because they can form a biofilm and provide the initial stage for further colonisation (Grandison et al. 2011).

Treatments with QACs should only be considered as an emergency solution to mussel fouling problems and cannot replace a MGPS as they do not seem to work equally well for different sized mussels. Piola & Grandison (2013, 2017) tested the effectiveness of commercially available QAC solutions in treating internal seawater systems affected by mussel fouling. Their field experiment showed that mussel size influenced the efficacy of the QAC solutions. Large mussels were killed by the treatment solutions, but smaller individuals were resilient to the varying treatment regimes. Changes in water temperature and increased exposure time did not enhance the efficacy of the treatment (Piola & Grandison 2013, 2017).

6.3.2.2.10 Non-biocidal treatments

Non-biocidal treatments for internal seawater systems are non-toxic. They include the following treatments to control biofouling which are described below. Refer to Jenner et al. (1998), Segnini de Bravo et al. (1998), Rajagopal et al. (2005b), Venkatesan & Murthy (2009), Grandison et al. (2011), Growcott et al. (2016) and de Castro et al. (2018) and references therein for more information on these treatments.

- **carbon dioxide (CO_2)**: induces a narcotic response in some fouling species (e.g. molluscs) and can be used a pre-treatment to make subsequent treatment with biocides more effective.
- **deoxygenation**: is the use of inert nitrogen gas to remove oxygen out of the water by forcing dissolved oxygen into the gaseous phase and creating a hypoxic environment for organisms; can reduce corrosion; there is no system for deoxygenation of internal seawater systems available; some species can tolerate extended periods of low oxygen and this method may stimulate anaerobic microbial growth; long exposure times required.
- **thermal shock**: is the killing of fouling organisms through thermal shock by flushing hot water through water systems; the temperature range and exposure time need to be sufficient as some species (e.g. blue mussel, Pacific oyster) have a great tolerance for thermal fluctuations; cannot be used for the feed into cooling systems; uniform exposure to whole system may be difficult to achieve and improper use may stimulate microbial growth; very effective against macrofouling but not against bacterial slime.
- **freshwater flushing**: involves flooding the internal seawater system with fresh water; the majority of marine fouling species receives a lethal osmotic shock due to hyposalinity; simple and environmentally friendly strategy for minimising and controlling sea chest fouling; freshwater dosing systems can be fitted on board; some organisms such as mussels can tolerate exposure to freshwater for up to several days; if the system is to run continuously, the amount of freshwater needed might be excessive and the cost prohibitive; water restrictions may hinder implementation of this strategy.

Researchers in New Zealand developed a novel thermal treatment apparatus for treating biofouling in the internal seawater system of recreational vessels. It was first tested in laboratory experiments using scale models of internal pipework configurations before applied in the field using recreational yachts. In the laboratory experiment the highly resilient sentinel test species *Magallana gigas* reached 100% mortality at a temperature of 60 degrees Celsius after 60 min. In the field study, those recreational vessels where an effective seal could be achieved, the water temperature could be maintained at a temperature >58 degrees Celsius for the duration of the treatment. When the internal seawater system of a vessel could not be effectively sealed, heat loss was excessive and treatment temperatures could not be maintained. As it was not possible to quantitatively assess biofouling viability in response to the treatment in the field (Cahill et al. 2019c,d), it can only be assumed that maintaining the water temperature at the desired level kills the biofouling organisms present in the pipework.

Electromagnetic fields applied to seawater to prevent the development of biofilm and biofouling in internal pipes or tubes of heat exchanger units and reverse osmosis membranes is an emerging environment friendly technology (Matin et al. 2021). Study results have been promising (e.g. Trueba et al. 2015), however, more scientific research is needed to validate whether this technology is effective in reducing biofilm development as suggested by the manufacturers of some commercialised devices (Piyadasa et al. 2017).

6.3.3 Cost of management practices

Both proactive and reactive measures incur costs to vessel owners. Any period that a commercial vessel is not in active service due to application of anti-fouling coatings or in-water cleaning activities results in costs that are associated with the procedure itself and the delays to its scheduled itinerary. A summary of the costs of the different types of measures and treatments is out of scope for this document but some high-level considerations will be presented in this section.

Floerl et al. (2010) and Inglis et al. (2012) provided cost estimates for removing biofouling on recreational and commercial vessels in Australia and New Zealand, respectively.

Based on quotes obtained by Floerl et al. (2010), charges for dry-dock hire and hull cleaning in Australia increase with the length of the vessel. The fees for dry-dock hire and equipment access represent the largest proportion of the total cost for small to medium sized vessels. For longer vessels, the cost of the cleaning activity (e.g. water-blast) is the most important cost item. Biofouling removal usually takes 1 day for smaller vessels and up to 3 days for larger vessels. If antifouling coatings are applied when the vessel is in dry-dock, another 3-7 days need to be added to the estimated duration (Floerl et al. 2010).

The following cost estimates are from 2010, so charges can be expected to be higher today. In 2010, for vessels longer than 200m in length (e.g. containerships) dry-docking and removal of biofouling from hull and niche areas cost A$ 195,000 plus three days of lost revenue. Renewal of the anti-fouling coating further increased the cost to A$ 425,000 plus seven days, or longer, of lost revenue. Costs for smaller vessels of up to 50m in length were lower. Biofouling removal cost A$ 26,400 and could be done in a day. Antifouling application on smaller vessels was estimated to take three days and cost an additional A$ 30,000 (Floerl et al. 2010).

In comparison, in-water cleaning using a diver-operated brush/blade cart system for in-water cleaning may take longer than dry-dock cleaning for removing biofouling on large commercial vessels such as containerships. Lewis (2013) estimated that the prototype system 'Envirocart' had the capability to clean 1,000 m^2 in a 6-hour day. If the cleaning system was operated for 6 hours a day then, based on an estimate of mean wet surface area of containerships (8,248 m^2, Moser et al. 2016), it would take one system around 8 days to in-water clean containerships. This time estimate does not consider the cleaning of internal niche areas which cannot be cleaned by this diver-operated system.

Floerl et al. (2010) also estimated the cost of in-water cleaning. For recreational vessels of about 12.5m length, in-water cleaning cost approximately A$ 240 (1-3 hours) for manual brushing/scrubbing and A$ 300-500 for encapsulation (1-4 days). The estimated in-water cleaning costs for large commercial vessels such as containerships varied by method. In-water cleaning methods could be ranked from lowest (A$ 14,000-24,000) to highest cost (A$ 81,300-97,800) as follows: Encapsulation (1-5 days) < rotating brush systems (4-5 days) < heat treatment robot system (3 days) < water-blast robot systems (3 days). However, encapsulation and heat treatment may need additional treatment to achieve fuel efficient propulsion as biofouling organisms are not removed from the vessel by these treatment (Floerl et al. 2010). This should also be followed by inspection to verify that no biofouling is present after treatments. Inglis et al. (2012) found the same pattern for vessels cleaned in New Zealand.

Based on the cost estimates from 2010, in-water cleaning was 10-50% cheaper for recreational vessels and 35-65% cheaper for commercial vessels (50-200m in length) than onshore cleaning (Floerl et al. 2010). The cost difference between in-water and dry-dock cleaning may be even more pronounced for commercial vessels because the number of places that provide dry-dock services is limited in Australia. If a vessel has to travel to Singapore for a dry-dock clean, it will incur further costs such as voyage delays and travel costs. Smaller vessels have access to more haul out facilities such as slipways and shiplifts (Rupert Summerson, pers. communication).

Economic considerations are important, but biosecurity risk management decisions also need to consider the practicality, feasibility and environmental impact of biofouling management options associated with non-compliant vessels. Haul out and cleaning, for example, remains one of the most viable options for most recreational and fishing vessels, but not for large vessels (Georgiades et al. 2020).

7 Conclusion

Marine biofouling is a complex problem. It is a biological process that is influenced by a range of factors that interact with each other. This review has presented current knowledge about how anti-fouling technologies, and vessel design and operating profile can affect the extent of vessel biofouling. It has also described the diversity of management practises that can be used to remove or control biofouling. However, these different aspects of biofouling are dynamic. It is still largely operational imperatives that drive the interest of the shipping industry in biofouling management, but major shifts in regulation (e.g., of toxic biocides) may bring significant changes to biosecurity management practices. The regulatory landscape is responding to the increasing volumes in trade and passengers and the significant biosecurity risks associated with biofouling while considering the economic interests of industry. Research undertaken by the higher education sector, government and industry will gain new insights into key processes of biofouling prevention and continue to advance and improve coatings and cleaning technology.

Niche areas remain a concern for biosecurity agencies due to their status as biofouling hotspots. Pragmatic solutions are needed to mitigate this biosecurity risk. Research and development should continue to investigate the relationship between vessel behaviour and biofouling, building and evaluating high quality data sets, by applying consistent and well-designed study approaches (experimental and in the field). This can facilitate creating risk profiles for arriving international vessels.

In-water biofouling removal or treatment is cheaper than onshore activities, but it has higher biosecurity and chemical contamination risks. Therefore, it is important to invest into research and development of innovative technology that can provide feasible and practical tools to owners of commercial and recreational vessels to remove or treat biofouling while protecting the marine environment from harmful chemical and biological waste. Field studies are important for testing new approaches for their efficacy in removing or treating biofouling, for a wide range of biofouling organisms (soft and calcareous), including mobile species. This can support the development and maintenance of thresholds and guidelines around in-water cleaning.

8 Glossary

Term	Definition
Anti-fouling coating (paint)	A coating (paint) applied to submerged surfaces to prevent or reduce accumulation of biofouling. Includes biocidal and non-biocidal coatings (paints). In this report 'coating' and 'paint' are used synonymously.
Biocide	A chemical substance incorporated into anti-fouling coatings to prevent settlement or survival of marine organisms.
Biofouling	The accumulation of aquatic organisms such as microorganisms, plants and animals on surfaces and structures immersed in or exposed to the aquatic environment.
Biosecurity	Activities to protect Australia's economy, environment and community from the negative impacts of pests and diseases entering, establishing or spreading in Australia.
Biosecurity risk	The potential harm to the economy, environment, human health and social and cultural values posed by pests and diseases entering, establishing or spreading in Australia.
Classification societies	Non-government organisations that establish and maintain technical standards (rules) for the construction and operation of vessels, including offshore structures. Classification societies classify and certify marine vessels and structures on the basis of their structure, design and safety standards. Vessels are surveyed for compliance with these standards.
Dry-dock	A basin in which vessels can be brought from a floating to a non-floating condition by pumping out the water in the basin. In the non-floating condition, the vessel is supported by blocks that are placed along specific dry-docking support strips on the bottom of the hull. Smaller vessels can be brought into a non-floating condition by lifting, using buoyancy forces on the vessel.
Exotic marine species	A species not known to be native to Australia
Floating dock	A mobile structure that can be used to raise a vessel out of water and serve as a dry-dock.
Introduced marine species	A species not native to Australia that is found in Australia as a result of human activity, whether by accidental or intentional release, escape, dissemination, or placement.
Invasive marine species	An introduced marine species that causes, or is likely to cause, unacceptable impacts to the environment, economy, human health, or social values.
In-water cleaning	The physical removal of biofouling and/or anti-fouling coating surface deposits from submerged surfaces. In this report, it also includes the elimination of biofouling organisms through various treatments. 'In-water' refers to the parts of a vessel or movable structure that are either below the load line or normally submerged.
Marine Growth Prevention System (MGPS)	An anti-fouling system used to prevent biofouling accumulation in sea chests and internal seawater systems. It includes the use of anodes, electrolysis, chemical dosing and copper/nickel pipework.
Niche areas	Areas on a vessel or movable structure that are more susceptible to biofouling accumulation due to different hydrodynamic forces, susceptibility to anti-fouling coating wear or damage or absence of anti-fouling coatings. For example, sea chests, bow thrusters, dry-docking support strips and rope guards.
Planned in-service period	The intended interval, decided at the time of anti-fouling coating application, until the next scheduled application of anti-fouling on a vessel or movable structure.
Proactive measures	Activities undertaken to prevent microfouling from forming, or to remove it from a vessel, or to prevent macrofouling from forming.
Reactive measures	Activities undertaken to remove or treat biofouling on vessel hulls and niche areas that has already advanced to the macrofouling stages.
Service life	The period of time an anti-fouling coating system is expected to protect a treated surface from biofouling and/or corrosion if the coatings are applied in accordance with the manufacturer's specifications.
Shiplifts	A mobile or fixed structure that can lift vessels out of the water vertically.

Term	Definition
Slipway	An inclined plane, sloping gradually down to the water, on which vessels can be hauled out of water.
Vessel	Any craft that operates in an aquatic environment for the purpose of transporting people or commodities, carrying out maintenance or providing a platform for other activities. For example, recreational, fishing, cruise, merchant, exploration, research or naval vessels, barges and other vessel types.

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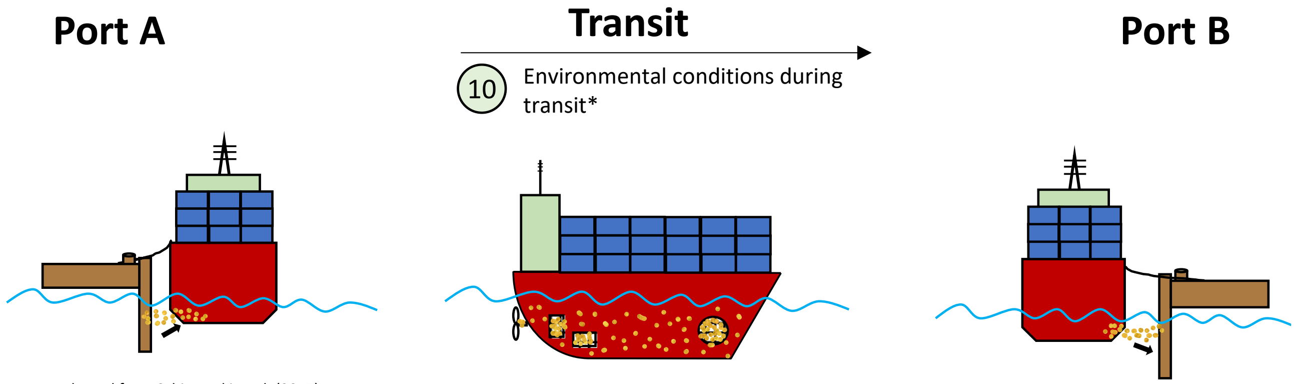
Appendix 1: Factors that influence vessel biofouling



Images adapted from Schimanski et al. (2017)

1. Vessel type* and activity
2. Number, size and complexity of niche areas*
3. Static time in port A and B and in previous ports*
4. Static time at anchorage*
5. Vessel speed and voyage duration
6. Biofouling Management Plan compliance
7. Anti-fouling coating age, condition and suitability
8. Marine Growth Prevention System
9. Hull husbandry

*These factors cannot be influenced by vessel management

Legend: Vessel characteristics and operational profile; Vessel biofouling management activities; Environmental conditions

(1) The nature of the operation or the inability to apply anti-fouling coatings of some vessel types is correlated with increasing the abundance of biofouling (e.g. dredges, oil rigs). The activity of vessels while they are visiting Australian waters influences the risk of spreading transferred exotic marine species domestically. The risk increases with visits to multiple ports.

(2) A greater number and size of niche areas provides a greater total area that can be colonized by biofouling organisms. Complex and difficult to clean niche areas are correlated with increasing the abundance of vessel biofouling.

(3) Longer static time in ports A and B and the number of previously visited ports is correlated with increasing the abundance of biofouling and the number of fouling species.

(4) Static time at anchorage over long periods is correlated with increasing the abundance of vessel biofouling.

(5) Faster vessels usually contain fewer biofouling organisms because hydrodynamic drag forces remove them. Slower vessels (<6 knots) are known to contain a greater number and diversity of fouling organisms. The use of foul release coatings is generally limited to faster vessels. The vessel route can influence the abundance of biofouling. If low-salinity environments are traversed the abundance decreases as exposure to freshwater kills marine organisms, but tolerances differ among species. Warmer temperatures promote biofouling growth. Longer vessel routes, including those across latitudes, limit or remove biofouling, especially when vessels travel from warmer to colder environments.

(6) Development of and adherence to a high-quality Biofouling Management Plan reduces the abundance of vessel biofouling.

(7) Anti-fouling coatings are designed to prevent biofouling. However, coatings that near the end of their expected service life or are damaged enable the attachment of biofouling organisms. Coatings not suitable for the operating profile are not effective in preventing biofouling.

(8) Marine Growth Prevention Systems are designed to prevent the accumulation of biofouling organisms, but their effectiveness is doubtful.

(9) Cleaning in water or in dry-dock removes biofouling organisms. There are different methods for removing or killing fouling species. In-water cleaning bears a biosecurity and environmental risk if removed fouling species are not captured effectively. In-water inspections determine the presence of exotic marine species.

(10) Fouling species are exposed to environmental stresses during transit such as fluctuations in temperature and salinity. Voyages within the same latitude and of shorter range may be less stressful for attached organisms and are correlated with higher levels of biofouling. In general, marine species from colder environments are more likely to establish in warmer or similar environments, but organisms from warmer environments are less likely to establish in colder environments.