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Manatū Ahu Matua

In-water cleaning technologies:
Review of information

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1 Executive summary

Vessel biofouling is a major pathway for the introduction of non-indigenous species into New Zealand's marine ecosystems. In-water cleaning is an important tool for reducing the biosecurity risks from this pathway during the in-service period of vessels. It can form part of a proactive biofouling management programme to reduce the accumulation of organisms on the vessel or be applied to remove biofouling growth from unmanaged vessels. However, the use of in-water cleaning carries some residual biosecurity risk which must be managed.

To conduct in-water cleaning it is necessary to understand the residual risk and to implement measures to mitigate it. This requires the testing and validation of proposed technologies for in-water cleaning and standard test requirements to guide decision-makers on when in-water cleaning should be permitted.

The purpose of this review is to develop an understanding of current and emerging technologies for in-water cleaning so that general methodological categories can be identified for the development of standard testing requirements. The review will also inform the requirements of the standard to be met by the cleaning methodologies.

Information found in recent reviews of in-water cleaning was updated by reviewing literature and reports published subsequently, and by contacting Australian and New Zealand companies with the capacity to conduct in-water cleaning. Company websites and video-sharing websites were also searched.

Methods for in-water cleaning fall into a discrete set of categories and subcategories, namely:

- manual technologies:
  - picking off organisms by hand;
  - hand cleaning with non-powered brushes, scrapers and scouring pads;
- mechanical technologies:
  - powered brush- or abrasive-pad based;
  - contactless;
  - high-pressure water jet;
  - cavitational water jet;
- surface treatment technologies:
  - heat;
  - ultrasonic;
- shrouding technologies:
  - encapsulation;
  - enclosure.

Many stages of the in-water cleaning and treatment processes discussed in this report are common to several method categories. Each stage has associated biosecurity risks:

1. Accessing the hull and moving among cleaning locations or enclosing the hull in a floating dock, shroud or wrapping, during which fouling, exfoliating paint and other material may be dislodged.
2. Cleaning of the water-line ("boot-top"), during which material may be ejected from the water and escape capture by the collection and filtration system, where fitted. Alternatively the boot-top may not be accessible for cleaning because the vessel is against a wharf or riding high out of the water after unloading cargo.
3. Cleaning of the general hull surface and efficacy of removal or treatment.

4. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) and efficacy of removal or treatment.
5. Containment, capture and extraction of waste material removed (where a capture system is fitted). Efficacy of material capture during cleaning and the integrity of the pumping system used to transfer waste to the treatment or disposal system.
6. Filtration of captured waste (where a filtration system is fitted) and efficacy of removal from the effluent stream to a minimum particle size. The smallest practically-achievable filtration standard seems appropriate for in-water cleaning, and currently this appears to be 12.5 µm. Alternatively, effluent may be treated (for example, with heat, UV light or biocides) or discharged to a sewerage system with secondary treatment.

If a cleaning method is to be used for ongoing hull maintenance, rather than only as an urgent-response tool, the effects of cleaning on antifouling coatings must also be considered in an assessment of the effectiveness of cleaning categories in reducing biosecurity risk. All categories of in-water cleaning methods have the potential to damage antifouling coatings, but assessment of damage is complicated and beyond the scope of this review. It is recommended that developers of cleaning equipment provide evidence that their equipment will not damage the types of paint that it is designed to clean. This evidence would be taken into account when approving cleaning technologies.

2 Introduction

Vessel biofouling is a major pathway for the introduction of non-indigenous species into New Zealand's marine ecosystems. According to the Ministry for Primary Industries' (MPI) Risk Analysis of Vessel Biofouling, these introductions can have significant economic and environmental impacts: http://www.biosecurity.govt.nz/files/regs/imports/risk/vessel-biofouling-risk-analysis-0211.pdf.

The risks associated with this pathway can best be mitigated by a proactive biofouling management programme as defined by the IMO guidance documentation: http://www.imo.org/blast/blastData.asp?doc_id=14217&filename=207%2862%29.pdf.

A key risk-management action identified in these guidelines is continual maintenance of the vessel's submerged surfaces, of which in-water cleaning is a key component. Further, the availability of in-water cleaning as a response option is important to reduce the risk of species establishment from unmanaged vessels. However, the use of in-water cleaning as a proactive or reactive measure carries some associated biosecurity risk which must be managed.

To understand and evaluate the risk posed by different in-water cleaning technologies, standard testing requirements need to be developed. These requirements, and associated guidance, would allow the independent evaluation of the efficacy of various in-water cleaning systems with respect to managing biosecurity risk.

The purpose of this review is to inform the development of standard testing requirements to evaluate different in-water cleaning technologies. Specifically, it provides an understanding of current and emerging technologies available for in-water cleaning to identify general methodological categories, rather than the details of each specific piece of equipment reviewed. These categories are the focus for the development of testing requirements.

Current in-water cleaning technologies follow two broad approaches:

- removal of the material from the hull (with or, more commonly, without capture of waste);
- treatments that kill the fouling organisms in situ and rely on subsequent movement of the vessel through the water to slough dead biofouling from the hull.

Each approach includes several different methodological categories and this review examines the key operational features of each of these categories. It identifies those stages of each category that have associated biosecurity risks and require testing.
The review will also inform the requirements of the standards to be met by the in-water cleaning technologies. These standards were defined by the Ministry for Primary Industries:

- removal methods – all biofouling shall be removed;
- treatment methods – all biofouling shall be rendered non-viable[1].

This document contributes to the scientific background for approval of in-water cleaning or treatment systems under the Craft Risk Management Standard for Biofouling for Arriving Vessels and within New Zealand's domestic biofouling management approach. The document will be considered along with other information in determining proposed measures that are practical to implement and align with all applicable legislation, while ensuring the biosecurity risk does not exceed New Zealand's appropriate level of protection.

[1] For the purposes of this review in-water cleaning technologies include both fouling removal and fouling treatment methods.

3 Methods

Information in the recent reviews of in-water cleaning technologies (Bohlander 2009; Floerl *et al.* 2010; Inglis *et al.* 2012; US DOT 2012; Morrisey *et al.* 2013) was updated by:

- reviewing literature and reports on in-water cleaning technologies available in Australia and New Zealand;
- contacting Australian and New Zealand companies with the capacity to conduct in-water cleaning, to gain a practical understanding of the equipment used / available (Appendix A – List of companies contacted for the review);
- contacting companies that produce or supply in-water cleaning technologies to gain a practical understanding of specific equipment used or in development (Appendix A – List of companies contacted for the review);
- reviewing company websites and promotional videos posted on video-sharing websites.

Manufacturers of antifouling coatings were also contacted to obtain advice on likely effects of cleaning methods on their products (Appendix A – List of companies contacted for the review).

4 Results and discussion

The categories and subcategories of in-water cleaning methods identified by the review are (Table 1):

- manual technologies:
  - picking off organisms by hand;
  - hand cleaning with non-powered brushes, scrapers and scouring pads;
- mechanical technologies:
  - powered brush- or abrasive-pad based;
  - contactless;
  - high-pressure water jet;
  - cavitational water jet;
- surface treatment technologies:
  - heat;
  - ultrasonic;
- shrouding technologies:
  - encapsulation;
  - enclosure.

The simplest technology is manual cleaning using hand-picking, soft pads, scouring pads, hand-held scrapers or brushes (“*manual technologies*”). This is often the principal method of cleaning for smaller vessels that operate under very different fouling-management regimes to larger, commercial vessels. For the purposes of the present study, techniques that remove fouling from the hull using powered tools are referred to as “*mechanical technologies*” and those that kill the fouling in situ as “*surface treatment technologies*”. One type of surface treatment involves encapsulating the vessel to reduce or eliminate water movement over the hull and thereby creating lethal conditions at the hull surface. Fouling organisms are killed either by adding a biocide to the water within the encapsulation or by allowing biological oxygen demand from organisms present on the hull and in the surrounding water to reduce dissolved oxygen to lethally-low concentrations. These methods as “*shrouding technologies*” in this report and they are dealt with separately from other surface treatments.

In keeping with the objectives of the review, individual cleaning systems have not been described, rather the focus is on describing the categories defined in the previous paragraph. However, individual systems have been described when they are currently the only example of a technology. For a list of individual, proprietary in-water cleaning tools and appliances, with descriptions of their features, see Appendix B – Examples of currently available cleaning technologies.

Table 1: Summary of in-water cleaning categories with stages of the cleaning process at which biosecurity risk may arise. 'Y'=yes, 'N'=no.

		Stages of cleaning process that may have associated biosecurity risk							
Category	**Subcategory**	**Set up[1]**	**Cleaning water-line[2]**	**Cleaning general hull[3]**	**Cleaning niche areas[4]**	**Edges[5]**	**Capture[6]**	**Filtration[7] (Int / Ext)[8]**	**Notes**
Manual	Hand-picking	Y	N?	Y			Y	Y?	Cleaning of niche areas and edges likely to be effective but cleaning of large areas of hull inappropriate. Water-line may be inaccessible on larger vessels. Volumes of water likely to be too small to require filtration unless suction capture is used.
	Hand-removal with brushes, scrapers and pads	Y	N?	Y	Y	Y	Y	Y	Cleaning of niche areas and edges likely to be effective but cleaning of large areas of hull inappropriate. Water-line may be inaccessible on larger vessels. Scrapers with capture systems are available and were used, for example, to remove fouling from the hull of a tug in the Port of Auckland in September 2012, with capture and filtration of waste to 50 µm.
Mechanical	Rotary brush / pad: hand-held devices	Y	Y	Y	Y	Y	Y	Y	Cleaning of niche areas and edges likely to be effective but cleaning of large areas of hull inappropriate. Water-line may be inaccessible on larger vessels. Prototypes with capture systems have been tested and commercial version is available, but not generally used.
	Rotary brush / pad: diver-operated brush carts	Y	Y	Y	Y	Y	Y	Y	Larger carts may not be effective on hull areas with sharp change of orientation, though some are articulated to address this. Most currently-used systems do not incorporate capture systems but many could be modified if market demand was sufficient.
	Rotary brush / pad: robot or ROV	Y	Y	Y	Y	Y	Y	Y	Larger devices may not be effective in hull areas with sharp change of orientation, though some are articulated to address this.
	Rotary brush / pad: contactless	Y	Y	Y	Y	Y	Y	Y	Currently available devices incorporate capture and filtration systems.

		Stages of cleaning process that may have associated biosecurity risk							
Category	**Subcategory**	**Set up[1]**	**Cleaning water-line[2]**	**Cleaning general hull[3]**	**Cleaning niche areas[4]**	**Edges[5]**	**Capture[6]**	**Filtration[7] (Int / Ext)[8]**	**Notes**
	High-pressure water jet: hand tools	Y	Y	Y	Y	Y	Y	Y	Cleaning of niche areas and edges likely to be effective but cleaning of large areas of hull inappropriate. Water-line may be inaccessible on larger vessels. Most currently-available devices do not incorporate capture and filtration systems but commercial versions are available.
	High-pressure water jet: cart / ROV	Y	Y	Y	Y	Y	Y	Y	Currently-available devices incorporate capture and filtration systems.
	Cavitational jet (self-propelled, diver-operated carts and hand-held pistols)	Y	Y	Y	Y	Y	Y?	Y?	Among currently-available models, hand tools do not generally have capture and filtration systems but some carts do. Unclear whether fouling organisms are killed by the force of cleaning, but assume not.
Surface	Hot water	Y	Y	Y	Y	Y	N (killed)	N (killed)	Larger devices appear not be effective in hull areas with sharp change of orientation. Application of hot water (> 57°C) by divers via a hose and nozzle was not effective in killing algal fouling on the hull of a tug in Tauranga Harbour (Stratford 2012) and the system has been upgraded to provide water at 110°C (Murray Wilson, Wilson Underwater Services Ltd., pers. comm.).
Shrouding	Encapsulation: floating docks and shrouds	Y	Y	N	N	N	N (killed)	N (killed)	If effective, the method will kill fouling in all areas of the hull with the exception of the water-line, where anoxia may not develop sufficiently. Verification that all fouling has been killed is critical.
	Encapsulation: wrapping	Y	Y	N	N	N	N (killed)	N (killed)	If effective, the method will kill fouling in all areas of the hull with the exception of the water-line, where anoxia may not develop sufficiently. Verification that all fouling has been killed is critical.

		Stages of cleaning process that may have associated biosecurity risk							
Category	**Subcategory**	**Set up[1]**	**Cleaning water-line[2]**	**Cleaning general hull[3]**	**Cleaning niche areas[4]**	**Edges[5]**	**Capture[6]**	**Filtration[7] (Int / Ext)[8]**	**Notes**
	Encapsulation with biocide	Y	Y	N	N	N	N (killed)	N (killed)	If effective, the method will kill fouling in all areas of the hull with the exception of the water-line, where anoxia may not develop sufficiently. Verification that all fouling has been killed is critical.
	Enclosure	Y	Y	Y	Y	Y	Y	Y	Same processes as whichever cleaning method is used within the enclosure, but allows use of tools without capture if water within the enclosure is filtered or treated before release.

[1] Diver and / or equipment accessing the hull and moving around, during which material may be dislodged.
[2] Suction or thrust may be lost at the air-water interface, reducing force of attachment of cleaner to hull and efficacy of waste capture.
[3] Cleaning of large, flat or moderately curved surfaces for which cleaning carts are best suited but hand tools may be inefficient.
[4] Cleaning of confined and / or difficult to access areas where fouling may be heaviest are often difficult for carts to clean effectively.
[5] Areas where the orientation of the hull changes sharply are often difficult for carts to clean effectively.
[6] Does the subcategory require that waste be captured and contained by suction or other means?
[7] Does the subcategory require that captured waste be filtered to an appropriate standard before discharge?
[8] Int = integrated filtration, i.e., in the submersible unit itself (likely to be small in volume), Ext = external filtration, i.e., piped to a surface unit (likely to be larger in volume and easier to increase in capacity).

4.1 MANUAL TECHNOLOGIES

Manual technologies may involve picking off target risk organisms by hand. This method has been used, for example, in managing incursions of *Styela clava* and *Sabella spallanzanii* on vessel hulls and fixed structures in Lyttelton, Nelson, Picton and Whangarei harbours. Because the method depends on divers visually detecting the target organisms, its effectiveness is influenced by water clarity and the amount of fouling present (both target and non-target organisms). Capture efficiency is likely to be high if organisms are enclosed in a bag or other container before removal. A suction system was used to collect *S. spallanzanii* hand-picked from barges in Coromandel Harbour (Kathy Walls, MPI, pers. comm.). The size of the incursion will limit the cost-effectiveness of this approach.

Manual scrubbing or wiping is the commonest method of in-water hull husbandry for recreational boats (Floerl *et al.* 2010). The type of tools used depend on the amount and type of fouling and on the type of antifouling coating applied. Cloths and pieces of carpet may be used on light, soft fouling (primarily microbial films and small algae) and where ablative coatings are used. Plastic or metal brushes or scrapers and scouring pads are used for heavier fouling or on hard coatings.

Manual cleaning may also be used on larger vessels to remove fouling from areas that cannot be reached by brush carts, ROVs and other larger equipment. Numerous manufacturers of brush-based and water jet-based devices offer a range of hand tools (Appendix B – Examples of currently available cleaning technologies) and these are discussed in Sections 4.2.1, 4.2.2, and 4.2.4. Two sizes of fully-enclosed, hand-held scrapers are available with waste collection and filtration (Franmarine Underwater Services: see Lewis 2013).

Wilson Underwater Services (WUS) Ltd. (Wellington) employ a scraper / vacuum system for manually removing biofouling. The scraper is a 150-mm broad knife (a plasterer’s trowel) semi-encased with a shroud that is attached to an inhalant vacuum pipe. The diver-operator controls the vacuum pressure to vary the volume of water entrained through the system. In the past, this system was used with a petrol-powered pump to generate the vacuum at the scraper nozzle. The vacuumed water and de-fouled material were pumped through a coarse filter and then heated using a diesel heating unit (described in Section 4.3.1), before discharge back to sea. This unit was not effective at the boot-top (air-water interface) because hydraulic pumps generally require a continuous supply of water for effective operation and any air entering the system can create an air-block and require the pump to be re-primed. Sequential filter systems, largely relying on gravity, are often used to filter water in order to avoid damaging fine filters by forcing water through them under high pressure. In the present context, the developer of the equipment considered that such filter systems would be difficult to operate effectively on the unstable platform of a vessel and if required to filter large volumes of water in order to keep up with the vacuum system (Murray Wilson, Wilson Underwater Services Ltd., pers. comm.). Consequently, WUS Ltd. now employ sewage vacuum trucks as the vacuum source for their manual system. The effluent is passed to the truck’s reservoir tank and subsequently disposed of at an appropriate facility (e.g., to sewer). This allows constant vacuum force to be supplied to the system, and avoids returning effluent to the sea. No tests on retention efficacy have been performed for this system. Use of vacuum trucks requires drive-to access to the cleaning location, or barging of trucks to the vessel to be cleaned.

Manual cleaning of a vessel can be made more biosecure by containing the process in a floating dock or shroud. This potentially provides a relatively cheap alternative to slipping a vessel where fouling is more than slime / biofilm and cleaning devices with collection systems are not available. This technique is discussed in Section 4.4.2. The biosecurity of this technology depends on maintaining the integrity of the dock or shroud.

Biosecurity risk may be associated with five stages of the set up and deployment of manual technologies (Table 1):

1. The diver(s) accesses the hull and moves among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the diver's movement or equipment (fins, surface-supply air hoses, etc.) or by the suction hose of the collection device (if used).
2. Cleaning of the general hull surface (generally this method would only be used on smaller vessels) and efficacy of removal.
3. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) and efficacy of removal.
4. Containment, capture and extraction of waste material removed (where a capture system is fitted). Efficacy of material capture during cleaning and the integrity of the pumping system used to transfer waste to the treatment or disposal system.
5. Filtration of captured waste (where a filtration system is fitted) and efficacy of removal from the effluent stream to a minimum particle size. Cleaning rates and filtration rates must correspond to avoid overloading filters. Alternatively, the waste may be treated to kill any organisms present by, for example, heating, adding chlorine compounds or exposing to UV light.

4.2 MECHANICAL TECHNOLOGIES

Traditionally, removal techniques, particularly for larger vessels, have used brushes in contact with the hull surface and / or fouling layer to remove fouling. The material of the brush varies with the type of fouling to be removed: nylon or polypropylene for slime, algae and soft-bodied organisms, stiffer plastics or steel brushes or abrasive pads to remove hard, calcareous organisms. Different brush materials are also used on different hull materials: nylon or polypropylene are used on fibreglass, aluminium, steel and wood: steel bristles are generally restricted to use on aluminium or steel hulls.

Other methods of removal include: rotating blades or brushes that create a lifting shear force over the hull surface without touching it, high-pressure water jets, and cavitational water jets. These methods are intended to reduce the adverse effects of abrasion on antifouling coatings, both to prolong the life of the coating and to reduce the amount of biocide released into the water column. Details on each of these are given below (Sections 4.2.2, 4.2.3 and 4.2.4).

4.2.1 Brush- or abrasive pad-based technologies

Brush-based cleaning ranges from small, hand-held devices to diver-controlled (but usually self-propelled) brush-carts, autonomous remote-operated vehicles (ROVs) and robot hull-crawlers. The use of soft cleaning pads and static brushes by divers has been considered in the section on manual methods however rotating, hand-held brush-heads are included here.

Hand-held devices

Hand-held devices (
Figure 1) are used by divers to clean smaller vessels, confined areas (*niche areas*) of the hulls of larger vessels, and to polish propellers. They may be powered hydraulically (via the support vessel's hydraulic system or via pumped seawater) or pneumatically, and can be fitted with various types of brush (e.g., silicone, polypropylene, nylon or steel), cutter blades or abrasive pads (See Appendix B – Examples of currently available cleaning technologies). Some hand-held devices may be operated manually from above the water surface, without the need for divers. For example, the Hulltimo Smart and Scrubmarine devices are both small single-head brush units attached to poles that can be operated by surface users to clean small vessels.

Most of these tools do not include collection and filtration systems for waste, although it would be possible to retrofit them or modify the design of at least some currently-systems (e.g., John Mitchell, La Mans Marine Engineering Pte Ltd., pers. comm.). The propeller-polishing tool (
Figure 1) has such a system, but currently this is only used by operators working in the port of Rotterdam (Syd Hutchinson, UMC International, pers. comm.).

Biosecurity risk may be associated with six stages of the set up and deployment of hand-held, brush-based devices (Table 1):

1. The diver(s) accesses the hull and moves among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the diver's movement or equipment (fins, surface-supply air hoses, etc.) or by the hydraulic or pneumatic hoses of the cleaning device.
2. Cleaning of the water-line ("boot-top"), during which material may be ejected from the water and escape capture by the collection and filtration system, where fitted.
3. Cleaning of the general hull surface (generally this method would only be used on smaller vessels) and efficacy of removal.
4. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) and efficacy of removal.
5. Containment, capture and extraction of waste material removed (where a capture system is fitted). Efficacy of material capture during cleaning and the integrity of the pumping system used to transfer waste to the treatment or disposal system.
6. Filtration of captured waste (where a filtration system is fitted) and efficacy of removal from the effluent stream to a minimum particle size. Alternatively, the waste may be treated to kill any organisms present by, for example, heating, adding chlorine compounds or exposing to UV light.

Diver-operated brush carts

These are, in effect, larger versions of the hand-held tools but may have more than one cleaning head, are self-propelled (with the diver providing steering and control of cleaning speed and force) and apply themselves to the hull surface by the thrust from propellers or suction created by the flow of water through the cleaning head (Figure 2). They are powered hydraulically (via the support vessel's hydraulic system or via pumped seawater) and can be fitted with various types of brush (e.g., silicone, polypropylene, nylon or steel), cutter blades or abrasive pads (see Appendix B – Examples of currently available cleaning technologies).

Most brush carts do not currently incorporate systems for collecting and filtering waste, although the Eco Hull Crawler (UCS, Spain) and the Envirocart (Franmarine, Australia) are exceptions (Appendix B – Examples of currently available cleaning technologies). Other manufacturers contacted indicated that they could provide capture systems if there was sufficient market demand (John Mitchell, La Mans Marine Engineering Pte Ltd., pers. comm.; Michael Gobin, Cybernetix, pers. comm.), while others were sceptical that development of such a system is practical or economically feasible (David Phillips, Hydrex, pers. comm.).

Figure 1: Examples of brush- or pad-based hand tools for hull and propeller cleaning. **Top left**: hydraulically-driven, self-propelled brush (300 - 400 mm diameter brush-head (source of photograph: Phosmarine Equipment website, www.phosmarine-brush-kart.com/hten/). **Top right**: hydraulically-driven propeller-cleaning brush (source of photograph: ArmadaHull website, www.armadahull.com/index.php). **Bottom right**: propeller-polishing using the SMS "Propduster" (source of photograph: Sub Marine Services Ltd. website, www.submarineservices.com/index.html). **Bottom left**: hydraulically-driven, single-brush cleaning and polishing tool which can be fitted with a brush or abrasive pad (source of photograph: UMC website, www.umc-int.com/).

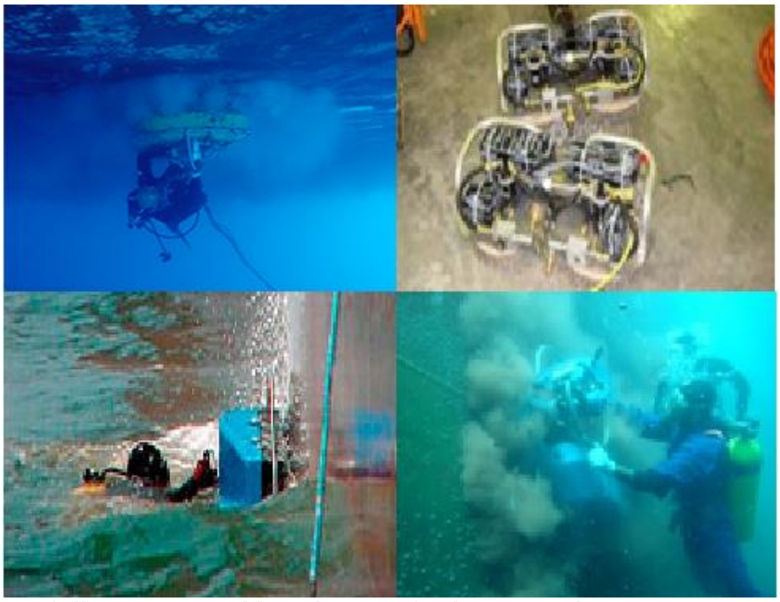

Figure 2: Examples of diver-operated brush carts for hull cleaning.
Top left: diver-operated, multi-brush cleaning cart (source of photograph: SubSea Global Solutions website, www.subseasolutions.com/ship-maintenance.php). **Top right**: diver-operated brush cart with triple brush-head (source of photograph: Lufesa Divers website, www.lufesa.com/hull_cleaning.html). **Bottom right**: waste dispersed into the surrounding water column during cleaning using a brush cart without a collection system (source of photograph: Piccard Divers website, www.piccard.gr). **Bottom left**: water and waste ejected above the water surface during cleaning of the boot-top using a brush cart (source of photograph: Piccard Divers website, www.piccard.gr).

A further refinement of the brush-cart system, the Mini-Pamper brush cart and twin-brush diver-operated systems (UMC International, United Kingdom) is described in Section 4.2.2. This transfers the suction created by the action of the brushes to the chassis, rather than the brushes, and thus minimises the application force of the brushes so that they travel over the hull without damaging the coating.

Biosecurity risk may be associated with six stages of the set up and deployment of diver-operated brush carts (Table 1):

1. The diver(s) accesses the hull and moves among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the diver's movement or equipment (fins, surface-supply air hoses, etc.) or by the hydraulic or pneumatic hoses of the cleaning device.
2. Cleaning of the water-line ("boot-top"), during which material may be ejected from the water and escape capture by the collection and filtration system, if fitted, (Figure 2) and adhesion to the hull (via propellers or water jets) may be less effective.
3. Cleaning of the general hull surface and efficacy of removal.
4. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) and efficacy of removal. Proprietary hull-cleaning systems may consist of a brush cart for cleaning the general hull surface and hand-held devices for cleaning niche areas.
5. Containment, capture and extraction of waste material removed (where a capture system is fitted). Efficacy of material capture during cleaning and the integrity of the pumping system used to transfer waste to the treatment or disposal system.
6. Filtration of captured waste (where a filtration system is fitted) and efficacy of removal from the effluent stream to a minimum particle size. Cleaning rates and

filtration rates must correspond to avoid overloading filters. Alternatively, the waste may be treated to kill any organisms present by, for example, heating, adding chlorine compounds or exposing to UV light.

Robotic or remotely operated vehicle (ROV) hull cleaners

These self-propelled, autonomous devices attach themselves to the hull surface by the thrust from propellers, by suction created by the flow of water through the cleaning head, or by magnets. Movement and cleaning activity is controlled from the surface via thrusters, on-board video cameras and positioning systems. The majority of systems currently available use water jets to clean (see Sections 4.2.3 and 4.2.4), but there are brush-based systems available. Others serve as equipment platforms for a range of purposes, including hull cleaning. They range in size from small, highly portable units, designed for cleaning recreational boats, to larger units designed to clean commercial vessels. The electrically-powered cleaning unit of the Hulltimo Smart, for example, measures 420 x 325 x 230 mm and weighs 5.7 kg while the ECA Roving Bat vehicle is twice the size and weighs 135 kg.

The Hulltimo cleaner models use a rotating brush with polyamide bristles and attach to the hull by suction. They are controlled via a tether and are designed to remove hard and semi-hard fouling and collect waste in a removable filter bag (mesh size 100 µm). The user-guide for the system warns against use without a bag because of possible serious damage to the robot.

Figure 3: Hulltimo Pro cleaning robot.
(source of photograph: Hulltimo website, www.hulltimo.com/fr/).

The US Office of Naval Research (ONR) is developing the brush-based robot Hull BUG (Hull Bio-mimetic Underwater Grooming) to groom and maintain the hulls of naval vessels. Hull BUG is tether-free, runs on a battery and uses a novel captive vortex created by an impeller to provide suction on to the hull. A further novel feature of Hull BUG is that on-board sensors allow the robot to avoid obstacles and to identify areas of fouling by detecting chlorophyll fluorescence. It does not incorporate a waste-capture system.

Figure 4: The US ONR's Hull BUG robotic cleaner.
The version shown does not include the fluorometric sensor for detecting biofouling (source of photograph: ONR website, www.onr.navy.mil/Media-Center/Fact-Sheets/Robotic-Hull-Bio-mimetic-Underwater-Grooming.aspx).

Biosecurity risk may be associated with six stages of the set up and deployment of robotic or remotely-operated brush carts (Table 1):

1. The ROV is manoeuvred up to and against the hull and is moved among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the ROV's movement or surface-supply hoses.
2. Cleaning of the water-line ("boot-top"), during which material may be ejected from the water and escape capture by the collection and filtration system, if fitted, and adhesion to the hull (via propellers or water jets) may be less effective.
3. Cleaning of the general hull surface and efficacy of removal.
4. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) and efficacy of removal.
5. Containment, capture and extraction of waste material removed (where a capture system is fitted). Efficacy of material capture during cleaning and the integrity of the pumping system used to transfer waste to the treatment or disposal system.
6. Filtration of captured waste (where a filtration system is fitted) and efficacy of removal from the effluent stream to a minimum particle size. Cleaning rates and filtration rates must correspond to avoid overloading filters. Alternatively, the waste may be treated to kill any organisms present by, for example, heating, adding chlorine compounds or exposing to UV light.

4.2.2 Contactless mechanical systems

Concern over damage to antifouling coatings (particularly silicone-based fouling-release coatings (FR)), and regulation of the discharge of biocidal waste into the surrounding environment, has led to the development of alternative approaches to removal of fouling that exploit sheer-forces generated by turbulent flow above the coating surface (Lewis 2013 and see Franmarine[2] and UMC[3] websites). These cleaning systems exploit the minimally adhesive properties of the coating surface and the effect of turbulent water flow in creating the shear force necessary to lift and dislodge any fouling from that surface. Effective FR coatings will remain free of fouling if the vessel is continually active and fast (> 10–15 knots) because of flow effects but, if the vessel is slow or has periods of inactivity, fouling will establish. Even with renewed activity, low-profile species will survive in the boundary layer against the hull where there is laminar, not turbulent, flow. If an organism grows upward, once it extends out of the boundary layer it may be dislodged by shear force caused by the turbulent flow.

Two currently-available systems exploit this cleaning method (Appendix B – Examples of currently available cleaning technologies). The Mini-Pamper brush cart and twin-brush diver-operated systems (UMC International, United Kingdom) use counter-rotating brushes to create suction that holds the cart onto the hull. However, the brush mountings transfer this force to the chassis rather than the brushes, and thus control the application force of the brushes so that they travel over the hull without damaging the coating. Earlier models used a blade-like system to create sheer force but this was subsequently changed to nylon bristles. An optional metal plough can be fitted to the front of the cart, above the surface, to slice through and remove heavy, erect fouling ahead of the brushes. The shrouded brush-head captures the waste and passes it to a filtration system which is claimed to capture and filter 75% of the waste removed.

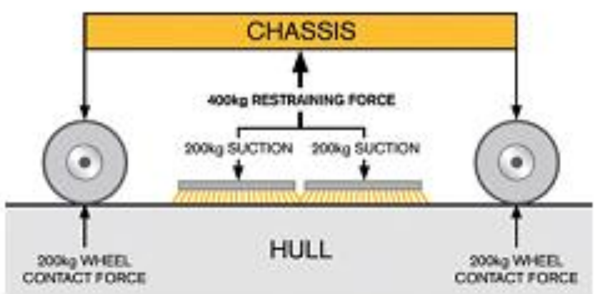

Figure 5: Mini-Pamper brush cleaning cart (UMC International).
Right-hand image shows how the downward suction force generated by the counter-rotating brushes is transferred to the chassis so that the brushes are only just in contact with the hull surface (source of photograph: UMC International website, www.umc-int.com/).

In response to a tender from the Western Australian Department of Fisheries, Franmarine Underwater Services (Western Australia) developed a cleaning system (the Envirocart) with rotating discs fitted with conventional brushes for hard paints (glass or epoxy-based) or blades for silicone- and copper-based paints (Lewis 2013). The latter operate on the contactless-cleaning principle. The system also includes fully-enclosed hand scrapers and an enclosed water-jet cleaner (the 'Magic Box') for cleaning niche areas. All of these tools can be operated in containment mode in which solids > 50 µm are removed in first-stage, screen filtration, then potentially to 5 µm in second-stage, cartridge filtration. Finally, the effluent is UV-sterilised. Filter cartridges rated to 25 µm are used in the second-stage filtration but these are

[2] www.gageroadsdiving.com.au
[3] www.umc-int.com

apparently capable of filtering to 5 µm (Lewis 2013); filtration to 12.5 µm has been achieved in trials (Justin McDonald, Western Australia Department of Fisheries, pers. comm.).

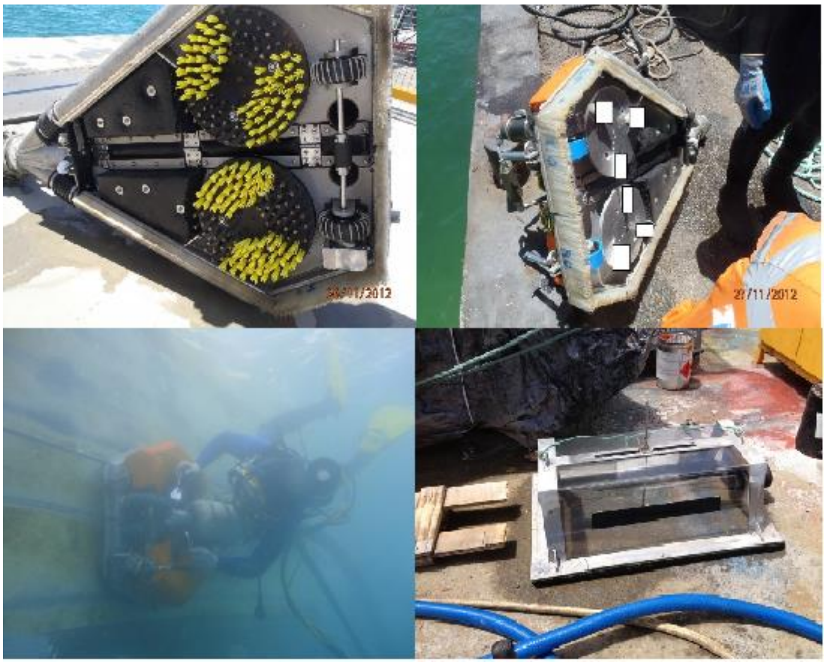

Figure 6: Franmarine Underwater Services' Envirocart cleaner.
Top left: fitted with rotating brushes. **Top right**: fitted with rotating blades for contactless cleaning (blades are obscured to protect commercial confidentiality). **Bottom right**: "Magic box" for cleaning anodes and other projections. **Bottom left**: Envirocart in use (source of photographs: Franmarine Underwater Services' website, www.gageroadsdiving.com.au/projects/envirocart/).

Whether by brushes (Mini-Pamper) or blades (Envirocart), the principle of contactless-cleaning is the same: create turbulent flow that causes the necessary shear force to dislodge the minimally adhesive fouling. For long-term static surfaces where there is vertical growth, the brush / blades will actually add a mechanical force to remove protruding growth. If the development of growth is due to lack of adequate "self-cleaning" water movement across a fouling-release surface, then water turbulence should clean it. However, if the surface has degraded and lost the surface properties that reduce organism adhesion strength, a non-contact system will not clean effectively.

Biosecurity risk may be associated with six stages of the set up and deployment of contactless mechanical techniques. These risks are essentially the same as those for other diver-operated brush carts (Table 1):

1. The cart is manoeuvred up to and against the hull and is moved among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the cart's movement or surface-supply hoses.
2. Cleaning of the water-line ("boot-top"), during which material may be ejected from the water and escape capture by the collection and filtration system, if fitted, and adhesion to the hull (via propellers or water jets) may be less effective.
3. Cleaning of the general hull surface and efficacy of removal.
4. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) and efficacy of removal.

5. Containment, capture and extraction of waste material removed (where a capture system is fitted). Efficacy of material capture during cleaning and the integrity of the pumping system used to transfer waste to the treatment or disposal system.
6. Filtration of captured waste (where a filtration system is fitted) and efficacy of removal from the effluent stream to a minimum particle size. Cleaning rates and filtration rates must correspond to avoid overloading filters. Alternatively, the waste may be treated to kill any organisms present by, for example, heating, adding chlorine compounds or exposing to UV light.

4.2.3 High-pressure water jet

Reduced damage to antifouling coatings and reduced release of contaminants to the environment (while still achieving the required level of cleaning) are benefits used to promote the use of high-pressure water jets over brush-based cleaning. For example, Cybernetix' Magnetic Hull Crawler uses jets at 1000 bar (100,000 kPa) (Michael Gobin, Cybernetix, pers. comm.). Providers of water-jet cleaners claim no loss of antifouling coating for systems using water under high pressure. Protection of the coating is achieved by directing the water jet at the hull surface at an angle < 90°, removing fouling via horizontal shear rather than a direct force applied perpendicular to the hull. There is, however, potential for coating damage if the equipment is not used appropriately. High-pressure cleaning in dry dock can remove antifouling coatings when not properly applied (John Lewis, ES Link Services Pty. Ltd., pers. comm.). Although the applied pressure may be lower during in-water cleaning, a high-pressure jet held close to and directly on a surface for too long will erode ablative or self-polishing coatings (John Lewis, ES Link Services Pty. Ltd., pers. comm.).

As with brush-based systems, water jet systems include hand-held devices, diver-operated carts and ROV or robot carts controlled from the surface via thrusters, on-board video cameras and positioning systems (Figure 7; Appendix B – Examples of currently available cleaning technologies). With hand tools, it is claimed that the direction of the jet can be altered by the diver to maximise cleaning force while avoiding damage to the antifouling coating. Some cart systems have adjustable water pressure to optimise cleaning effectiveness versus protection of the antifouling coating, monitored during cleaning by the operator via CCTV cameras. Again, these systems may be capable of damaging coatings if not used appropriately. Additional water jets may be used to hold the cart or ROV against the surface to be cleaned, including countering the back-thrust from the cleaning jets.

The ROV-based systems, and also Franmarine's "Magic Box" cleaning system for niche areas (see Section 4.2.2), incorporate collection and filtration systems. ECOSubsea's prototype cleaning system collected and filtered (150 µm) > 95% of waste removed in independent trials (Liltved 2012), though this was based on cleaning simulated, rather than actual, fouling (wood particles incorporated into a latex-paint coating on steel plates). Other manufacturers claim, apparently without providing evidence, that, for example, "all residues are collected and disposed of".

Figure 7: GAC EnvironHull's HullWiper hull-cleaning ROV.
(source of photograph: GAC website: www.gac.com/gacen/service.aspx?id=59651).

Biosecurity risk may be associated with six stages of the set up and deployment of high-pressure water jet cleaning techniques (and the potential biosecurity risks associated with them). These risks are essentially the same as those for equivalent brush-based systems (i.e., diver operated, carts and ROVs: Table 1):

1. The diver(s) accesses the hull and moves among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the diver's movement or equipment (fins, surface-supply air hoses, etc.) or by the hydraulic or pneumatic hoses of the cleaning device.
   Alternatively, the cart or ROV is manoeuvred up to and against the hull and is moved among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the cart's movement or surface-supply hoses.
2. Cleaning of the water-line ("boot-top"), during which material may be ejected from the water and escape capture by the collection and filtration system, if fitted and adhesion to the hull (via propellers or water jets) may be less effective.
3. Cleaning of the general hull surface and efficacy of removal.
4. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) and efficacy of removal.
5. Containment, capture and extraction of waste material removed (where a capture system is fitted). Efficacy of material capture during cleaning and the integrity of the pumping system used to transfer waste to the treatment or disposal system.
6. Filtration of captured waste (where a filtration system is fitted) and efficacy of removal from the effluent stream to a minimum particle size. Cleaning rates and filtration rates must correspond to avoid overloading filters. Alternatively, the waste may be treated to kill any organisms present by, for example, heating, adding chlorine compounds or exposing to UV light.

However, there are likely to be differences in the effects of cleaning on the antifouling coating and possibly on the level of cleaning achieved. Water jets may allow better access and cleaning to restricted and niche areas than brush-based tools, although this depends on how close to the surface the jet nozzle can reach, since pressure drops off rapidly with distance.

4.2.4 Cavitational water jet

A refinement of the water-jet method is the use of water jets incorporating microscopic bubbles of air and steam, generated by ultrasonic sound. Like contactless methods of cleaning, cavitational jets were developed to reduce damage to antifouling coatings and also to reduce the hazard to operators of using high-pressure jets. The pressure of the cavitational water jet (120–150 bar (12,000–15,000 kPa)) is significantly less than that used in conventional water-jet cleaning but the bubbles are claimed to collapse on contact with the surface treated, creating very high, localised pressures "destroying" and removing organisms, rust and exfoliated paint without damaging underlying paint. It is unclear whether cavitational jets actually kill fouling beyond dislodging it and breaking it up (which may not kill smaller propagules or organisms capable of regeneration). Cavitational jets are capable of eroding ablative or self-polishing antifouling coatings if held too close and directly on a surface, as evidenced by loss of coatings in high-cavitation areas on rudders and around propellers and thrusters during normal vessel movement (John Lewis, ES Link Services Pty. Ltd., pers. comm.).

A range of tools is available, including hand-held pistols, diver-propelled and self-propelled carts, and one company has a robot-based system in development (Figure 8). Suction systems to collect waste are incorporated in the larger units from at least one manufacturer (there is no reference to these systems being connected to a filtration system on the company’s website, but presumably this is feasible). The Limpieza Purotecnica SA website[4] refers to a system in development for “collection, transportation and utilization” of marine fouling and particles of paint and anti-corrosive coating. This is likely to be the same system (Cavi-Jet Net) referred to by Floerl *et al.* (2010), which incorporates a net installed beneath the hull of the cleaned vessel to collect waste as it sinks through the water column.

[4] www.uk.cavi-jet.com/4/index.html

Figure 8: Examples of cavitational-jet cleaning equipment.
Top left: wheeled, diver-operated cleaning head (source of photograph: CaviDyne LLC website, www.cavidyne.com/home.shtml) **Top right**: cleaning pistol for cleaning curvilinear surfaces and niche areas, with reactive nozzle to compensate for recoil and cleaning-rate regulator (source of photograph: Limpieza Putotecnica SA website, www.uk.cavi-jet.com/4/index.html#demp). **Bottom right**: prototype robot cleaning head (source of photograph: Limpieza Putotecnica SA website, www.uk.cavi-jet.com/4/index.html#demp). **Bottom left**: self-propelled **cleaning head** (source of photographs: Limpieza Putotecnica SA website, www.uk.cavi-jet.com/4/index.html#demp).

Biosecurity risk may be associated with six stages of the set up and deployment of cavitational water jet cleaning techniques. These risks are essentially the same as those for equivalent brush-based and high-pressure water-jet systems (diver-operated, carts and ROVs: Table 1):

1. The diver(s) accesses the hull and moves among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the diver's movement or equipment (fins, surface-supply air hoses, etc.) or by the hydraulic or pneumatic hoses of the cleaning device.
   Alternatively, the cart or ROV is manoeuvred up to and against the hull and is moved among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the cart or ROV's movement and surface-supply hoses.
2. Cleaning of the water-line ("boot-top"), during which material may be ejected from the water and escape capture by the collection and filtration system, if fitted and adhesion to the hull (via propellers or water jets) may be less effective.
3. Cleaning of the general hull surface and efficacy of removal.
4. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) and efficacy of removal.

5. Containment, capture and extraction of waste material removed (where a capture system is fitted). Efficacy of material capture during cleaning and the integrity of the pumping system used to transfer waste to the treatment or disposal system.
6. Filtration of captured waste (where a filtration system is fitted) and efficacy of removal from the effluent stream to a minimum particle size. Cleaning rates and filtration rates must correspond to avoid overloading filters. Alternatively, the waste may be treated to kill any organisms present by, for example, heating, adding chlorine compounds or exposing to UV light.

However, there are likely to be differences in the effects of cleaning on the antifouling coating and possibly on the level of cleaning achieved. Cavitational jets may allow better access and cleaning to restricted and niche areas than brush-based tools.

4.3 SURFACE TREATMENT TECHNOLOGIES

4.3.1 Heat treatment

Heat treatment has been used to manage incursions of non-indigenous marine species, including *Undaria pinnatifida* in New Zealand (Wotton *et al.* 2004; Stuart *et al.* 2008). All of the currently available methods for applying heat use the same general protocol, although the means for generating heat varies. Consequently, all are considered together in this section of the report.

Treatment of *Undaria* on the hull of a sunken trawler in the Chatham Islands (Wotton *et al.* 2004) was carried out using a wooden "hot-water box" containing heating elements supplied with electricity from a surface support vessel. The box was placed against the hull by divers and foam seals around the edges prevented exchange of water with the surroundings. Water was heated to 70°C within 15 minutes and this temperature was maintained for 10 minutes (trials had shown that this exposure was effective in killing the sporophytes of *Undaria*). A vent at the top of each box allowed expanding water and steam to overflow into a filter bag (mesh size not specified) to contain any dislodged gametophytes. A Petrogen flame torch was used to treat the areas of the hull where the box could not be applied closely to the hull due to bent or curved plating, for inaccessible areas of the vessel, such as near the seafloor, and for areas with heavy fouling. No sporophytes were recorded during a post-treatment survey of the vessel 18 months later.

A proprietary version of the hot-water box is currently available and uses heat (70°C) to kill fouling on the laminar-flow sides of a vessel (Hull Surface Treatment (HST)[5]). Heat is applied via a square applicator with soft skirt surround to contain the heated water and prevent loss of material before it is treated. The applicator moves autonomously over the hull and does not require divers to apply it. Hot water is provided from a surface support vessel. Fouling is left on the hull and, in theory, sloughs off when the vessel is in motion.

Trials of the HST system on two Royal Australian Navy vessels found that less than 50% of the hull could be reached and / or treated by the HST unit, mainly because of the orientation angle of large parts of the hull (Richard Piola, Defence Science and Technology Organisation, Australia, pers. comm.). Of those areas that could be reached, about 15% remained untreated

[5] www.tcmarine.com.au/HST

because of smaller-scale irregularities of shape, presence of appendages and other factors. The unit was not able to treat algal growth along most of the wind-water line. In those areas that could be treated, fouling was reduced and algae killed but follow-up studies are required to determine whether fouling is sloughed off after treatment (to reduce drag and fuel consumption) and how quickly regrowth or recolonisation of treated surfaces occurs.

The HST system is not designed to remove heavy fouling but, rather, to be applied regularly (e.g., twice a year) to keep fouling to a minimum (e.g., slime and algae). A modification of the system, in the form of a blanking plate, has been developed to treat vessel sea chests by heating the water within the sea chest to lethal temperature (Leach 2011). The HST system is claimed not to harm antifouling coatings ("No damage to... or removal of... existing antifouling paints"[6]), but this is not necessarily accepted by manufacturers of antifouling coatings (David Baker, International Paint Ltd., pers. comm.; Shaun Mizis, Akzo Nobel Pty. Ltd., pers. comm.; Antonio García Ordinaña, Hempel Ltd., pers. comm.).

Blakemore and Forrest (2007) trialled a system to direct steam or heated water from a surface-based industrial steam cleaner onto the treatment surface via a flexible silicone cone (30-cm diameter) that contained the hot water over the substratum, also as a control method for *Undaria*. Water was heated at a much faster rate than in the hot-water box (above), with a heating rate of ca 1.4°C second^{-1} on flat surfaces but ca 1.0°C second^{-1} on irregular surfaces. The maximum temperature achieved on both surfaces was about 55°C (ambient 19°C). Survivorship of *Undaria* on the treatment surfaces was 0–6% and that of macrofouling (sponges, tubiculous polychaetes, barnacles, bryozoans and ascidians) was 9% and 15% for flat and irregular surfaces, respectively. A relatively small, flexible cone was used in the trials because the system was intended for use on irregular natural substrata but Blakemore and Forrest (2007) concluded that the technique was not sufficiently consistent for use in controlling *Undaria* on such surfaces. For flat areas, such as the hull of a vessel, however, a better heat-seal may be achievable and with a larger treatment area, making the technique potentially more suitable than the slower electrical heating of water.

Wilson Underwater Services (WUS) Ltd. (Wellington) employed heat treatment on the hull of the tug *Katea*, imported from Australia as part of the response to the grounding of the container ship *Rena* off Tauranga. The hull of the tug was discovered on arrival to be fouled with, among other organisms, the invasive red alga *Grateloupia filicina*. The treatment used divers to pump hot water over biofouling to kill the target species and other biofouling. Following treatment, the biofouling may be left in situ or removed with a scraper / vacuum system (see Section 4.1). Freshwater, rather than seawater, can be used to add an additional biocidal treatment. Water is heated on the deck of a tender vessel using a diesel heating system similar to those used in commercial steam cleaners. The continuous flow of low-pressure (e.g., 20 L min^{-1}) hot water is then pumped through a rubberised hose to a nozzle. The diver directs the water from the nozzle over the biofouling for the desired treatment time. Since the trial on the *Katea* in December 2011, WUS Ltd. have increased the water temperature from 70°C to 110°C (because it is under water, the heated water remains as a liquid rather than as steam) (Murray Wilson, Wilson Underwater Services Ltd., pers. comm.).

For the treatment of the *Katea*, divers were requested to treat each area of fouling for at least three times longer than the time it took to observe any colour or structural changes in the biofouling. Observations and video footage taken during the treatment operation on the *Katea*

[6] www.tcmarine.com.au/HST

suggested that the hot water treatment effectively denatured the blades and filaments of algal species fouling the hull and waterline of the *Katea* (Stratford 2011). However, this was not qualified through follow-up data / observation to validate treatment efficacy. A follow-up survey of *Katea* in Auckland in August 2012 (Wilkens *et al.* 2012) showed the continued presence of *Grateloupia filicina* and a range of other biofouling organisms, suggesting that the heat treatment had not been effective.

Further heat-treatment of the hull of the *Katea* was done in September 2012 by a different contractor and using a different method (a refined version of the "hot-water box" used on the trawler in the Chatham Islands), but the details of this work are currently commercial-in-confidence.

In terms of the stages involved in applying these heat-based treatments, they are broadly similar to those of the other treatments discussed so far, namely: positioning the equipment on and moving around the hull and effective treatment of fouling in those areas the technique is intended to treat. In the case of heat treatments, however, treatment of the boot-tops is likely to be as effective as that of other flat areas of the hull. Treatment of curved areas of the hull and niche areas requires use of either different heat-based methods, such as flame torches (Wotton *et al.* 2004), or different methods of cleaning (e.g., brush-based or water-jet-based). Floerl *et al.* (2010) reported that Commercial Diving Services (the developers of HST) were developing a heat-based system to treat fouling in niche areas, in the form of a diver-operated device. This HST Niche Applicator is also capable of treating more developed fouling than HST itself, with the diver able to adjust the operating temperature between 50 and 90°C. No information on testing of this equipment was available at the time of the Floerl *et al.* (2010) report, and there is currently no mention of it on the HST website[7].

Because fouling organisms are killed in situ, collection and filtration is not required from a biosecurity perspective but verification that the treatment standard (i.e., all biofouling shall be rendered non-viable) has been achieved is crucial. Species may vary in the temperature and period of exposure required to kill them. Taxa with thick, calcareous shells or tubes, for example, may be insulated from heat. The amount of fouling may also alter the effectiveness of heat treatment by reducing water movement and penetration of hot water to the hull surface. There is also a risk that fouling will be dislodged during manipulation of the equipment against the hull before treatment.

Biosecurity risk may be associated with three stages of the set up and deployment of heat treatment technologies (Table 1):

1. Divers access the hull and movie among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the divers' movement or equipment (fins, surface-supply air hoses, etc.) or by the hot-water hoses of the cleaning device.
   Alternatively, heat-application equipment is manoeuvred up to and against the hull and is moved among cleaning locations, during which fouling, exfoliating paint and other material may be dislodged from the hull by the equipment's movement and hot-water hoses.
2. Cleaning of the general hull surface and efficacy of treatment.

[7] www.tcmarine.com.au/HST, accessed 9 April 2014

3. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) by supplementary methods and efficacy of treatment (or collection, containment and filtration if not heat-treated).

4.3.2 Ultrasonic treatment

Ultra-sound is sound pressure waves that have a frequency greater than the upper limit of human hearing (normally > 20 kHz). Ultrasound is used for cleaning in surface-treatment industries (Mazue *et al.* 2013). Different ultra-sonic frequencies inhibit biofouling in different ways: by elevating temperature, by ultra-sonic wave-induced force, by ultra-sonic cavitation or through a combination of these mechanisms (Guo *et al.* 2011). In laboratory settings, cavitation has been shown to inhibit bacterial growth, barnacle settlement, and to remove algae and biofilms. Cavitation occurs at relatively high acoustic pressures (> 20 kPa) and is much stronger at lower ultra-sound frequencies (19–23 kHz) (Guo *et al.* 2011). Barnacle larvae are killed by relatively short (5 minutes) exposure to these high acoustic pressures (Seth *et al.* 2010; Guo *et al.* 2011). However, cavitation does not occur at low acoustic pressure (< 5 kPa), and Guo *et al.* (2012) showed that barnacle larvae were not killed by sound frequencies of 23 kHz or greater.

Mazue *et al.* (2013) tested an experimental ultrasonic cleaning station in which two cleaning heads were placed either side of a 15-m long vessel and moved slowly over the hull. Each cleaning head consisted of a cluster of ultrasonic transponders surrounded by a brush. As fouling was removed it was directed by the brush to a suction system for collection and treatment.

A number of companies currently market ultrasonic transducers that attach to the hull and are claimed to prevent recruitment and establishment of fouling organisms. The sales material for one such system states that "(t)he system produces a complex ultrasonic pattern creating an overpressure situation that bursts vacuoles in cells of algae and other organisms that adhere to the hull, thereby killing those organisms while not harming fish, marine mammals, humans or the boat's hull."[8]. Although this implies that such systems could be used to kill fouling organisms in addition to discouraging recruitment, the manufacturers do not suggest this and at least one recommends that the hull be cleaned before fitting the system (see the Aqua Sonic Management Pty Ltd. website[9]).

These commercially-available techniques have not been assessed for their ability to remove fouling and are not currently marketed for this purpose. However, Northland Regional Council are currently conducting trials of the effects of ultrasound on adult *Sabella spallanzanii*, in collaboration with DSS Ecotech Ltd. (New Zealand distributors for Aqua Sonic Managements Pty Ltd's transducer systems). In initial laboratory trials, there was 100% mortality of *Sabella* after 3 days. However, the role of the ultrasound treatment was confounded by potential effects of water temperature and concentration of dissolved oxygen (Irene Middleton, Northland Regional Council, pers. comm.). Subsequent trials in larger aquaria (3000 L) with flow-through seawater have not yet shown any effects on *Sabella* mortality. All worms were alive and apparently healthy after 5 days, suggesting that temperature and oxygen concentration may have caused the effects observed in the first study.

[8] www.aquasonicmanagement.com
[9] www.aquasonicmanagement.com

In the later trial, four 50-W transducers, with emission frequencies up to 120 kHz, were running continuously over 5 days (details of the equipment are proprietary to DSS Ltd).

4.4 SHROUDING TECHNOLOGIES

Shrouding techniques involve enclosing the vessel hull in an impermeable membrane to reduce or eliminate water exchange between the area immediately around the hull and the surrounding water, and thereby deprive fouling organisms of oxygen, food and light. Methods of achieving this include wrapping, or encapsulating, the hull in plastic sheeting. Biocidal, oxygen-scavenging compounds or freshwater can be added to the water inside the shroud to increase the speed of treatment effect. These methods have the significant advantage that, if water movement is maintained within the shroud, they will potentially treat all areas of the hull, including niche areas, with similar effectiveness. Alternatively, shrouding can involve enclosing the boat within a floating dock or shroud that surrounds the entire hull up to the water-line while the hull is cleaned manually or mechanically.

4.4.1 Encapsulation

Floating docks and shrouds

Several companies manufacture floating docks (also known as 'slip liners') for keeping recreational boats in when they are not being used in order to reduce the development of fouling. These provide the logistically simplest means of shrouding. The docks have a floating (for example, air-filled) collar with a flexible plastic membrane suspended from it that forms a completely enclosed, water-filled compartment. The back end of the dock can be opened or lowered to allow the vessel to enter and then raised to enclose it. Boats enter under their own power or can be towed in. Water can be pumped out of the dock to further reduce the amount of water in contact with the hull. In a hull-cleaning context this would also reduce the required amounts of any materials added to increased rates of mortality. A wide range of vessel sizes can be accommodated (FAB Dock, for example, claim their product is "(a)vailable for any size or shape of boat": www.fabdock.com). The use of a floating dock to treat fouling by *Sabella spallanzanii* on the hull of an 8-m yacht in Auckland is described in the section on *Addition of biocides and accelerants,* below).

These floating docks are intended for ongoing hull maintenance use, however they may also be suitable as an urgent response treatment. This is a point of contrast with wrapping methods. Note that fouling may develop on the outside of a floating dock if it is left in the water for an extended period. However, it is unlikely to be moved to a different location in this condition.

At least one specialised version of a floating dock has been specifically designed for treating hull fouling (the Introduced Marine Pest Protector, IMProtector™ developed by Biofouling Solutions Pty Ltd[10]). The shroud is deployed around the boat, rather than the boat being driven into it, but this can be done from a small dinghy or the vessel itself and does not require divers. These systems can currently accommodate vessels up 18 m long and 5 m draft and can be deployed on vessels in a marina berth, alongside a wharf or at anchor. Larger

[10] www.biofoulingsolutions.com.au

versions are planned, including a version for semi-submersible oil rigs[11], but have not yet been built (Nick Gust, Biofouling Solutions Pty Ltd., pers. comm.).

Trials of the IMProtector suggest that when the vessel is left within the shroud, anoxia lethal to all fouling organisms develops within nine days (Floerl *et al.* 2010). In the case of yachts, mortality can develop within 4–5 days, possibly because these vessels are more likely to use antifouling coatings that release biocides into the water inside the shroud. Further the surface area of the hull from which leaching can occur may be larger relative to the volume of water within the shroud than for larger vessels.

Because shrouds can be deployed in more exposed situations than floating docks, and because they are generally made of lighter materials to make them more easily deployable, shrouds may be more subject to damage during harsh weather.

Wrapping

Wrapping differs from use of a floating dock or shroud because, rather than fully enclosing the vessel in a single "bag", enclosure is achieved by wrapping a strip of material round and round the structure. The overlapping margins are usually sealed with adhesive tape and the condition of biofouling on the hull can be assessed by cutting holes in the wrap and then resealing them with tape. Because it generally uses less robust material than floating docks and shrouds, wrapping is more suitable for urgent response treatment of existing fouling, rather than for ongoing hull maintenance, although more robust wrapping material, suitable for deployments of weeks rather than days, are available (Bruce Lines, Diving Services New Zealand Ltd., pers. comm.). Wrapping with rolls of polythene sheeting has been used extensively in New Zealand on wharf pilings, rip-rap rock wall, moorings and other structures to control nuisance marine species, particularly the ascidian *Didemnum vexillum* in the Marlborough Sounds (Coutts and Forrest 2007). It has also been used to treat, albeit unsuccessfully, a 113-m long ex-naval frigate prior to it being scuttled to serve as an artificial reef off Wellington (Denny 2007). Trials have also been conducted in South Australia and Western Australia[12].

Wilson Underwater Services Ltd. use large ripstop (canvas) tarpaulins to shroud vessels and structures because they find these more durable than silage-wrap, and better for insulation if combined with hot water treatment. Once shrouded, vessels or structures are left for several days to let anoxia kill the biofouling, or target organisms may be removed by hand via divers (e.g., their recent treatment of a *Sabella spallanzanii*-infested yacht in Wellington). Acetic acid may be used as an additional biocidal treatment. Anoxic seawater is then removed from within the shrouding via a petrol-powered pump, and also via the heat treatment system described in Section 4.3.1, to allow removal of the shrouding and retention and disposal (to landfill) of any biofouling that has fallen from the vessel or structure. No tests on treatment efficacy have been performed for this system.

Stages in the application of the method are similar to those for floating docks or shrouds but because the enclosure is not continuous, there is more risk of exchange of water and propagules with the surrounding water body. The need for divers to wrap the material around

[11] www.biofoulingsolutions.com.au/featured-projects/enclosure-treatment
[12] See www.fish.wa.gov.au/Sustainability-and-Environment/Aquatic-Biosecurity/Vessels-And-Ports/Pages/Vessel-Encapsulation-Devices.aspx

the hull and the fact that enclosure is achieved progressively as wrapping proceeds means that there is also greater risk of material being dislodged and not captured within the enclosure. A collection system may be required to collect material dislodged during wrapping.

Addition of biocides or accelerants

The rate of decrease in oxygen concentration within the shroud can be accelerated by the addition of oxygen-scavenging chemicals. This approach also provides a greater level of control of concentrations of dissolved oxygen. Deoxygenation of water using sodium metabisulphite and / or hydrogen sulphide has apparently been used in cooling water systems for the control of zebra mussels, *Dreissena polymorpha* (studies cited by Clearwater *et al.* 2008), but Clearwater *et al.* (2008) recommended sodium sulphite for controlling freshwater pest species in New Zealand because of its ease of use, low toxicity to humans and lack of residual toxicity. Sodium sulphite combines with oxygen to produce sodium sulphate, with no by-products or change in pH (Clearwater *et al.* 2008). Trials would be needed to establish the required dose to achieve anoxia, but Clearwater *et al.* (2008) give indicative minimum application rates.

Natural development of anoxia due to respiration of microorganisms can be enhanced by the addition of respiratory substrates such as sugar, molasses, whole milk or lactose (Clearwater *et al.* 2008). The method is cheap, easy to monitor (by measuring dissolved oxygen) and there is no residual toxicity. However, overdosing could lead to the discharge of a body of water with high biological oxygen demand at the end of the treatment if there is limited dispersion by water currents.

A number of biocides have been used to enhance treatment of fouling using shrouding, including acetic acid and dissolved chlorine compounds. During attempted eradication of *Didemnum vexillum* in the Marlborough Sounds, numerous vessels (size range 7–30 m) were enclosed with custom-shaped polythene sheets and acetic acid added to achieve a 5% working concentration (Pannell and Coutts 2007). After 7 days, the treatment was found to have been completely effective at killing *D. vexillum*. A similar method was used to treat floating pontoons colonised by the solitary ascidian *Styela clava* in a marina in the Waitemata Harbour (Coutts and Forrest 2005). Mortality of all *S. clava* present took 10 minutes of exposure to 1% acetic acid inside the shroud or 6 days with no addition of chemicals. Apart from oysters (*Crassostrea gigas*) and calcareous tubeworms (*Pomatoceros terranovae*), complete mortality of all fouling taxa present was achieved after 20 minutes exposure to 1% acetic acid. Chlorine compounds were less effective at accelerating mortality, probably because of deterioration of free active chlorine[13] levels from the target of 200 mg L^{-1} to < 1 mg L^{-1} over the course of the 12-hour exposure.

Northland Regional Council has recently collaborated with NIWA to test the use of a floating dock to treat *Sabella spallanzanii* on the hulls of recreational vessels. Chlorine compounds were added to the water in the dock to increase the effectiveness of the treatment. In addition to the response of the worms to the biocide, the study also measured concentrations of free active chlorine and dissolved oxygen at 16 places on the hull (including niche areas) to determine concentrations at the point of contact over the course of the treatment. The target initial concentration of 200 mg L^{-1} FAC was achieved around the keel but all parts of the hull

[13] Free active chlorine is the sum of hypochlorous acid (HOCl) and hypochlorite ions (OCl^-).

were exposed to concentrations of at least 100 mg L^{-1} at some point during the treatment (NIWA and Northland Regional Council, unpublished data). Sixteen hours after the chlorine was added, the concentrations at all locations on the hull had dropped to between 1 and 3 mg L^{-1}. Of 30 worms sampled from different parts of the hull at the end of the treatment (16 hours after the addition of dissolved chlorine), all had lesions on their bodies and damaged or missing fans. Six days after the treatment, none of the 33 *Sabella* tubes collected from the hull contained worms. Other fouling organisms, including oysters and mussels, also appeared to have been killed, though these were not assessed in detail. Dissolved oxygen concentrations remained above 77% throughout the treatment, indicating that this was unlikely to have contributed to mortality over the 16-hour course of the treatment.

In April 2014, a yacht carrying *Sabella spallanzanii* was treated on arrival in Nelson by wrapping in plastic sheeting and adding acetic acid to the enclosed water (Bruce Lines, Diving Services New Zealand Ltd., and Javier Atalah, the Cawthron Institute, pers. comm.). The wrapping material was a commercially-available plastic silage cover (details are commercial-in-confidence to New Zealand Diving and Salvage Ltd). Water quality inside the wrapping was monitored over the course of the treatment using probes lowered into the encapsulated space (putting divers inside the wrapping was considered too hazardous: Bruce Lines, pers. comm.). Following addition of 5% acetic acid to the encapsulated water at the start of the treatment, pH and concentration of dissolved oxygen (DO) decreased from ca 7.5 and 8 mg L^{-1}, respectively, to ca 5 and 6 mg L^{-1} over the course of 5 days. After a further addition of acetic acid, pH decreased to ca 4 and DO to 1 mg L^{-1} 6 days from the start of treatment. DO remained at this concentration, presumably as organisms killed by the acetic acid decomposed.

Where biocides are added, niche areas and parts of the hull distant to the location where the biocide is added may experience lower (and possibly non-lethal) concentrations than more accessible areas of the hull because of reduced water movement around them. Conversely, if biofouling is to be killed by the development of anoxia, niche areas and deeper parts of the hull are likely to experience lethally low oxygen concentrations more rapidly for the same reason. The duration of treatment should take these factors into account and any surveys to verify that fouling organisms have been killed should include these areas of the hull.

Biosecurity risks associated with encapsulation treatments

Biosecurity risk may be associated with five stages of the set up and deployment of encapsulation technologies (Table 1):

1. Moving the vessel into the dock, or deploying the shroud around the vessel, during which the flexible nature of the side walls means that they may rub against the hull and potentially dislodge fouling that may fall outside the dock.
   In the case of wrapping, the scope for dislodgement of fouling during deployment is considerably greater and because enclosure is achieved more gradually, there is also greater risk that dislodged material will escape enclosure.
2. Closure of the point of entry to enclose the vessel within the dock. If this is done simply by lowering part of the surface collar to allow the boat to enter and then raising it again, the seal will be complete, with minimal risk of exchange of water with the surrounding water body (which would dilute the biocidal effects of enclosure and allow release of propagules). If it is done by closing a seam in the curtain, the quality

of the seal will influence the effectiveness of treatment, and this is particularly important for wrapping.

3. Pumping water out of the dock to increase the rate of development of anoxia or reduce the amount of biocide required to achieve effective concentrations. Water should be filtered or otherwise treated before discharge back to the sea to prevent release of organisms or propagules.
4. Treatment, either by allowing dissolved oxygen to fall to lethal concentrations as a result of respiration by the organisms on the hull and in the water within the dock, or by addition of biocides or oxygen-scavenging compounds. Duration of treatment, and the effective concentrations of oxygen or biocides within the dock, will determine the efficacy of the treatment.
5. Verification of the efficacy of the treatment on general areas of the hull and niche areas before the vessel leaves the dock or wrapping is removed, after which fouling may be cleaned off or erode as the hull moves through the water. This could be done by examination of fouling organisms and / or by monitoring concentrations of oxygen or biocides achieved within the fouling assemblage and comparing these with known lethal values. Verification may be difficult with wrapping because of the lack of space between the hull and the membrane.

4.4.2 Enclosure systems

The floating dock and shrouding systems described in Section 4.4.1 can also be used in conjunction with mechanical or manual removal of fouling to contain waste removed during the cleaning process. In these systems, divers or remotely-operated carts or cleaning ROVs are deployed within an enclosure system. When cleaning is finished, the material can be left in the dock to die as a result of developing anoxia or collected via a suction pump (some proprietary floating docks include an integral pump system) and filtered out before the water is discharged back into the sea. The space between the hull and the dock membrane must be large enough that divers can operate safely and effectively within it and that there is minimal risk of the cleaning equipment tearing the membrane.

In this mode, and with adequate waste treatment, enclosure would allow the use of mechanical and manual cleaning systems that do not incorporate collection and filtration systems within the cleaning unit. They could also provide additional biosecurity for surface treatments by minimising the risk that fouling dislodged during deployment of equipment escapes treatment. Poor visibility caused by suspended waste within the shroud may reduce the efficacy of cleaning.

Material cleaned off the hull could be treated by adding a biocide to the water after cleaning and before the enclosure is opened, to ensure that no viable material is released to the surrounding environment.

Biosecurity risk may be associated with seven stages of the set up and deployment of enclosure technologies (Table 1):

1. Moving the vessel into the dock, or deploying the shroud around the vessel, during which the flexible nature of the side walls means that they may rub against the hull and potentially dislodge fouling that may fall outside the dock.
2. Closure of the point of entry to enclose the vessel within the dock. If this is done simply by lowering part of the surface collar to all the boat to enter and then raising it

again, the seal will be complete, with minimal risk of exchange of water with the surrounding water body (which would dilute the biocidal effects of enclosure and allow release of propagules). If it is done by closing a seam in the curtain, the quality of the seal will influence the effectiveness of treatment.

3. Cleaning of the general hull surface and efficacy of removal.
4. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) and efficacy of removal. Proprietary hull-cleaning systems may consist of a brush cart for cleaning the general hull surface and hand-held devices for cleaning niche areas.
5. Integrity of the enclosure during cleaning.
6. Capture and extraction of waste material removed (where a capture system is fitted). Efficacy of material capture during cleaning and the integrity of the pumping system used to transfer waste to the treatment or disposal system.
7. Filtration of captured waste (where a filtration system is fitted) and efficacy of removal from the effluent stream to a minimum particle size. Cleaning rates and filtration rates must correspond to avoid overloading filters. Alternatively, the waste may be treated to kill any organisms present by, for example, heating, adding chlorine compounds or exposing to UV light.

4.5 COMPATIBILITY OF IN-WATER CLEANING WITH ANTIFOULING COATINGS

Ongoing minimisation or removal of fouling are important components of a vessel's fouling management system. Minimisation of fouling development depends on maintaining an effective antifouling coating in good condition. This may be compromised by some in-water cleaning techniques, particularly if they are not applied appropriately. The significance of reduced antifouling performance depends on the reasons for in-water cleaning. Three scenarios illustrate these reasons:

1. Arrival of a heavily-fouled vessel at a port of first entry, requiring urgent management of gross general fouling.
2. Arrival of a vessel with patchy fouling (for example, of niche areas), including patchy fouling of identified unwanted species.
3. Routine cleaning to maintain minimal fouling on the hull.

Damage to the antifouling coating is relatively unimportant in scenario 1 because the coating has clearly failed, and the imperative is to reduce the biosecurity risk[14]. Under the other two scenarios, however, the coating may be performing adequately over much or all of the hull, and cleaning may impair that performance and increase biosecurity risk in the long term. Vessel owners are likely to object to in-water cleaning that reduces the life of the coating. From the vessel owner's perspective, this is also important because damage to the coating may affect the paint manufacturer's warranty. For these reasons, damage to coatings may affect take-up of a cleaning technology by vessel owners. Furthermore, in addition to reducing fouling, the various layers of paint on a vessel's hull also play a role in preventing hull corrosion (Shaun Mizis, Akzo Nobel Pty. Ltd., pers. comm.). Reduction in anti-corrosion protection will be detrimental to vessels under all three scenarios. In order to achieve good, sustainable fouling management it is therefore desirable that in-water cleaning should not compromise the performance of the coating.

[14] The Anti-fouling and In-water Cleaning Guidelines (http://www.agriculture.gov.au/biosecurity/avm/vessels/anti-fouling-and-inwater-cleaning-guidelines) advise that in-water cleaning should not be performed on vessel that have reached or exceeded the planned in-service period of their antifouling coating, but exceptions can be made to address a biosecurity hazard.

Possible causes of damage include physical abrasion of coatings by brush-based or water-jet-based systems. A high-pressure jet held close to, and directly on, a surface for too long will erode ablative or self-polishing coatings (John Lewis, ES Link Services Pty. Ltd., pers. comm.). The operating temperature of some heat-based treatments is at the upper boundary of tolerance for most self-polishing antifouling coatings on the market (David Baker, International Paint Ltd., pers. comm.; Shaun Mizis, Akzo Nobel Pty. Ltd., pers. comm.; Antonio García Ordinaña, Hempel Ltd., pers. comm.). Heat may affect self-polishing copolymers more than other types of antifoulant, but effects of short-term exposure to heat are likely to be reversible (Colin Anderson, American Chemet Corporation, pers. comm. to John Lewis, ES Link Services Pty. Ltd.).

Further research is needed on the use of encapsulation techniques on different hull surfaces and coatings to ensure that the technique does not have any unanticipated effects (Inglis *et al.* 2012). Altered, potentially extreme conditions (in terms of ionic concentrations and pH) created by the addition of biocidal compounds may change the performance of antifouling coatings, at least in the short term. Long-term effects are also possible but unknown (John Lewis, ES Link Services Pty. Ltd., pers. comm.). Self-polishing copolymers are more sensitive to changes in their chemical environment than controlled-depletion polymers because of effects on the process of hydrolysis by which biocides are solubilised and released (Colin Anderson, American Chemet Corporation, pers. comm. to John Lewis, ES Link Services Pty. Ltd.). Silicone-based, biocide-free antifoulants are unlikely to be affected by chemical changes.

Changes in pH caused, for example, by the addition of acetic acid to the water, are likely to change the behaviour of the antifouling coating (Pritesh Patel, International Paint Ltd., pers. comm.). A strong acid or alkaline environment is likely to affect the reaction chemistry of both the hydrolysis and dissolution of the paint matrix and the release of copper (John Lewis, ES Link Services Pty. Ltd., pers. comm.). The leaching rate of copper from cuprous oxide-based paints may change by about 25% for a change of 0.1 pH units (Robinson 1957), being faster at lower pH values (at least within the pH range of seawater). The leaching rate also decreases with the square of salinity, so that in a mixture of equal parts of seawater and freshwater the rate will be 25% of its value in full-strength seawater (35 psu) (Robinson 1957).

Formation of insoluble copper salts will also impair antifouling performance. High concentrations of dissolved hydrogen sulphide in polluted estuaries in southeast Asia caused failure of antifouling coatings on vessel hulls due to reaction of sulphide with free copper released from the coating to form insoluble copper sulphide (John Lewis, ES Link Services Pty. Ltd., pers. comm.). Creation of anoxic conditions during encapsulation could potentially lead to development of similarly high concentrations of hydrogen sulphide.

Paint manufacturers see a potential advantage in water jet or cavitational jet cleaning over conventional brush-based cleaning for silicone-based coatings and are working with equipment suppliers to develop these methods (Antonio García Ordinaña, Hempel Ltd., pers. comm.). However, for reasons of cost and experience with the technology, brush-based cleaning remains the current market standard. Abrasive cleaning also rejuvenates self-polishing coatings.

From the perspective of developing a testing framework for in-water cleaning techniques, assessment of effects on the antifouling coating is probably limited to inspection for visible damage. Other approaches are potentially feasible, such as measuring biocide release rates or coating thickness before and after cleaning. However, these are not simple to apply because of the large number of confounding factors involved, the difficulty in defining controls, and the practical difficulties of the tests.

In the present context, the most straightforward approach would be to require the developer of the cleaning system under test to provide confirmation from paint manufacturers that potential adverse effects on antifouling coatings were unlikely. This confirmation could be based on pre-tests of cleaning effects done in collaboration with the coating manufacturers and for some types of cleaning equipment would be specific to particular types of coating. Minimal delay to testing would occur if this information was available at the time that a request for biosecurity testing was submitted. At present, cleaning companies do not usually consult with paint companies about the effects of their methods on antifouling coatings (David Baker and Pritesh Patel, International Paint Ltd., pers. comm.; Shaun Mizis, Akzo Nobel Pty. Ltd., pers. comm.). However, for foul-release coatings, such as International Paints' Intersleek, developers of cleaning equipment have contacted the paint manufacturers to test their equipment and, if they can demonstrate cleaning without scratching, they are added to a list of companies and equipment shown to clean that coating successfully (Pritesh Patel, International Paint Ltd., pers. comm.).

4.6 IN-WATER CLEANING STANDARDS

The objectives for in-water cleaning are that for mechanical methods, all visible, macroscopic biofouling shall be removed. For surface treatment and shrouding methods, all biofouling shall be rendered non-viable. In the case of mechanical methods, however, there is a second critical step, namely capture and treatment of waste after removal from the hull. An appropriate (and achievable) standard of biosecurity is also needed for this. This section considers information on the standards achievable with current methods of in-water cleaning.

Divers may miss patches of fouling when manually cleaning, and Floerl *et al.* (2008) found that 80% of recreational vessels cleaned in this manner three weeks previously had fouling on their hulls (including non-indigenous species). The same is true for divers using rotational brushes, especially when cleaning niche areas (Hopkins *et al.* 2008).

Trials with prototype, diver-operated brushes, with suction devices to capture waste, removed up to 100% of soft fouling on a vessel hull and up to 93% on curved and flat test panels (Hopkins *et al.* 2008, 2010). On average, 5% of the fouling removed was not captured. Cleaning efficiency generally decreases as the level of fouling increases, particularly for calcareous organisms (up to 61% of hard taxa remained after test cleaning: Hopkins *et al.* 2008). Trials of SCAMP (fitted with polypropylene bristles and with polypropylene bristles with steel inserts) on a heavily-fouled vessel reduced the fouling cover from 89% to 37% (Davidson *et al.* 2008). Following cleaning, 81% of species (30 out of 37) were still present. SCAMP also left behind colonies of unicellular algae and basal parts of larger algae, particularly on rougher surfaces (Moss and Marsland 1976).

Encrusting clonal organisms, such as bryozoans, can survive cleaning on heavily-fouled surfaces and subsequently regrow and reproduce sexually or by fragmentation (Davidson *et* *al.* 2008). Baseplates and shells of calcareous organisms that remain after cleaning can provide a substratum for chemo-induction of recruitment (Anil *et al.* 2010).

Capture and removal or treatment of waste from in-water cleaning is critical because cleaning does not kill all the organisms removed. Fragmentation and dislodgement plays an important role in natural dispersal of some algae and clonal organisms. In experimental trials of diver-operated brushes, Hopkins *et al.* (2008) found that 8% of the material not collected by the suction system was viable. This material was in addition to that knocked off the hull by the divers' fins and hoses and other gear dragged across the hull while using the brushes. Woods *et al.* (2007) reported that up to 70% of organisms removed by hand scrapers during in-water cleaning was viable.

In establishing standards for filtration, the capability of different filtration methods must be considered. In sediment studies, 50 µm seems to be the limit for filter screens, and cartridge systems are needed to remove particles smaller than this (John Lewis, ES Link Services Pty. Ltd., pers. comm.). Cartridge filters rated to 1 µm are available, providing a possible standard pore-size. However, rate of filtration may impose a larger practical limit because rate of filtration decreases with filter pore-size, requiring filters to be run in parallel and changed frequently to prevent overloading. Trials of a filtration system with the Franmarine Envirocart, under the supervision of the Western Australian Department of Fisheries, suggests that filtration to 12.5 µm is achievable (Justin McDonald, WA Department of Fisheries, pers. comm.).

The suction collection system used by Coutts (2002) to remove *Didemnum* from vessel hulls passed the effluent through a 200 µm pre-filter and into a second pre-filter chamber where 100 µm and 200 µm filters were tested for effectiveness. A second, in-line pump then passed the water through a filter-bag in which pore sizes of 1–200 µm were tested for retention of suspended solids. Successful filtering down to 50 µm was achieved at the third stage, but filters with smaller mesh all failed (i.e., particles larger than the pore size were found in the filtered effluent).

Various pore sizes have been proposed for filtration of waste from in-water and on-shore cleaning of fouling. The IMO Ballast Water Convention Guidelines for Ballast Water Sampling has performance standards of 50 µm and 10 µm[15], and the Australian and New Zealand *Anti-fouling and In-water Cleaning Guidelines*[16] state that "(i)n-water cleaning technologies should aim to, at least, capture debris greater than 50 µm in diameter". McClary and Nelligan (2001) recommended 60 µm to contain all mature organisms and the majority of propagules of the 43 target species identified in their study of on-shore cleaning. This size has been adopted in MPI's guidelines for the treatment of waste from wash-down facilities for vessels arriving in New Zealand from overseas[17].

McClary and Nelligan's (2001) recommendation of a pore size of 60 µm for treatment of waste from hull cleaning was based on the assumption that smaller propagules, notably spores of *Undaria pinnatifida* (10 µm diameter), were unlikely to survive conditions in typical shore-based cleaning facilities. Other species of macroalgae have even smaller spores (2 µm:

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[15] IMO Resolution MEPC.173(58) Guidelines for Ballast Water Sampling (G2), available at www.imo.org/blast/blastDataHelper.asp?data_id=23757&filename=173(58).pdf

[16] Available at http://www.agriculture.gov.au/biosecurity/avm/vessels/anti-fouling-and-inwater-cleaning-guidelines

[17] Guidance Document to the Standards for General Transitional Facilities for Uncleared Goods, as amended and reissued 1 September 2011, available at www.biosecurity.govt.nz/border/transitional-facilities/bnz-std-tfgen

Clayton 1992). Survival of these propagules may be better during in-water cleaning, partly because they are released into seawater rather than on to a wash-down area where temperature, salinity and other variables are likely to be more variable and mechanical shock more likely. Consequently, a smaller filtration standard seems appropriate for in-water cleaning and, based on systems tested so far, the 12.5 µm standard achieved with Franmarine's Envirocart appears to be the smallest size of filtration currently achievable.

As an alternative to filtration (or following preliminary, coarse filtration), effluent may be treated (for example, with heat, UV light or biocides) or discharged to a sewerage system with secondary treatment. Further options are that the effluent be processed through sand filters or discharged directly to the ground more than 100 m from the sea (or waterway or drainage system), and on permeable ground that is able to absorb all discharged water and where there is no likelihood that it could flow back to the sea within two days (consistent with MPI's standards for facilities for the on-shore removal of biofouling from vessels).

5 Conclusions

5.1 CATEGORIES OF IN-WATER CLEANING

Methods for in-water cleaning fall into a discrete set of categories and subcategories, namely:

- manual technologies:
    - picking off organisms by hand;
    - hand cleaning with non-powered brushes, scrapers and scouring pads;
- mechanical technologies:
    - powered brush- or abrasive-pad based;
    - contactless;
    - high-pressure water jet;
    - cavitational water jet;
- surface treatment technologies:
    - heat;
    - ultrasonic;
- shrouding technologies:
    - encapsulation;
    - enclosure.

Research for this review suggested that there is disagreement among proponents of different categories of cleaning regarding the relative merits of each. However, these disagreements do not appear to be supported by rigorous testing.

5.2 BIOSECURITY RISK ASSOCIATED WITHIN STAGES OF EACH IN-WATER CLEANING CATEGORY

Many stages of the in-water cleaning and treatment processes discussed in this report are common to several method categories. Each stage has associated biosecurity risks:

1. Accessing the hull and moving among cleaning locations or enclosing the hull in a floating dock, shroud or wrapping, during which fouling, exfoliating paint and other material may be dislodged.

2. Cleaning of the water-line ("boot-top"), during which material may be ejected from the water and escape capture by the collection and filtration system, where fitted. Alternatively the boot-top may not be accessible for cleaning because the vessel is against a wharf or riding high out of the water after unloading cargo.
3. Cleaning of the general hull surface and efficacy of removal or treatment.
4. Cleaning of niche areas and edges (where the orientation of the hull changes drastically) and efficacy of removal or treatment.
5. Containment, capture and extraction of waste material removed (where a capture system is fitted). Efficacy of material capture during cleaning and the integrity of the pumping system used to transfer waste to the treatment or disposal system.
6. Filtration of captured waste (where a filtration system is fitted) and efficacy of removal from the effluent stream to a minimum particle size. The smallest practically-achievable filtration standard seems appropriate for in-water cleaning, and currently this appears to be 12.5 µm. Alternatively, effluent may be treated (for example, with heat, UV light or biocides) or discharged to a sewerage system with secondary treatment.

5.3 COMPATIBILITY OF CLEANING METHODS WITH ANTIFOULING COATINGS

For ongoing hull maintenance, the effects of cleaning or treatments on antifouling coatings must also be considered as part of an assessment of the effectiveness of cleaning categories in reducing biosecurity risk. This is likely to be best achieved by discussion, and possibly testing, between the developer of the cleaning technology and paint manufacturers at an early stage of technology development.

5.4 FILTRATION STANDARD

The propagules of algae and other fouling taxa can be as small as 2 µm (Clayton 1992), and the smallest practically-achievable filtration standard seems appropriate for in-water cleaning. Based on systems tested so far, 12.5 µm appears to be the smallest size of filtration currently achievable.

As an alternative to filtration (or following preliminary, coarse filtration), effluent may be treated (for example, with heat, UV light or biocides) or discharged to a sewerage system with secondary treatment.

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8 Appendix A – List of companies contacted for the review

Company / provider	Country	Cleaning category				Contact	Response	Website
In-water cleaning		***Mechanical***	***Surface***	***Shrouding***	***Manual***			
Alldive Ltd	Malta	X				Website / Email	N	www.alldiveltd.com
ArmadaHull	USA	X				Website / Email	N	www.armadahull.com
Biofouling Solutions Pty Ltd	Australia			X		Ashley Coutts and Nick Gust	Y	www.biofoulingsolutions.com.au
Cybernetix Business Unit Oil & Gas	France		X			Michael Gobin	Y	www.cybernetix.fr
Defence Science and Technology	Australia					Richard Piola	Y	www.dsto.defence.gov.au
Diving Services NZ	New Zealand			X	X	Bruce Lines	Y	www.divingservicesnz.com
ECA Robotics	France		X			Website / Email	N	www.eca-robotics.com
Franmarine Underwater Services	Australia	X	X		X	Roger Dyhrberg via John Lewis (ES Link Services)	Y	www.gageroadsdiving.com.au
Hulltimo	France	X				Website / Email	N	www.hulltimo.com
Hydrex	Belgium, USA, Spain	X				David Phillips (USA) and Boud Van Rompay (Belgium)	Y	www.hydrex.be
La Mans Marine Engineering	Singapore	X				John Mitchell	Y	www.lamansmarine.com
Lufesa Divers	Peru	X				Website / Email	N	www.lufesa.com
Nick Segredakis Diving	Greece	X				Website / Email	N	www.nsdltd.gr
Northern Underwater Technical Services	New Zealand				X	Matt and Kathy Conmee	Y	www.divecom.co.nz
NZ Diving and Salvage	New Zealand		X		X	Dougal and Sol Fergus	Y	www.nzds.co.nz
Phosmarine Equipment	France	X				Website / Email	N	www.phosmarine-brush-kart.com
Piccard Divers	Greece	X				Website / Email	N	www.piccard.gr
Scamp	Gibraltar	X				Website / Email	N	www.scampnetwork.com

Company / provider	Country	Cleaning category				Contact	Response	Website
In-water cleaning		***Mechanical***	***Surface***	***Shrouding***	***Manual***			
Seahorse Diving Inc.	USA	X				Website / Email	N	www.seahorsediving.com
Sub Marine Services	UK	X				Website / Email	N	www.submarineservices.com
Submarine Manufacturing & Products Ltd. (SMP Ltd)	UK	X				Website / Email	N	www.smp-ltd.co.uk
Subsea Global Solutions	USA, Panama, Netherlands, Italy	X	X			Website / Email	N	www.subseasolutions.com
Underwater Contractors Spain (UCS)	Spain	X	X			Paw Jakobsen	Y	www.ucspain.com
UMC International	UK	X				Syd Hutchinson	Y	www.umc-int.com
Wilson Underwater Services Ltd	New Zealand		X	X	X	Murray Wilson	Y	http://www.wilsonunderwater.com
Antifouling coatings								
Akzo Nobel Pty. Ltd., / International Paints Ltd.	Australia, New Zealand, Singapore	N / A	N / A	N / A	N / A	Shaun Mizis and Aaron Lines (Akzo Nobel), David Baker / Pritesh Patel (International Paint)	Y	www.akzonobel.com
Greencorp Marine	Australia	N / A	N / A	N / A	N / A	Ian Hawkins	N	www.greencorpmarine.com
Hempel Ltd.	Denmark, New Zealand	N / A	N / A	N / A	N / A	Marianne Pereira and Antonio Garcia Ordinaña	Y	www.hempel.com
Hydrex Coatings	Belgium, USA, Spain	N / A	N / A	N / A	N / A	David Phillips (USA) and Boud Van Rompay (Belgium)	Y	www.hydrex.be

9 Appendix B – Examples of currently available cleaning technologies

Category	Subcategory	Providers	Videos available on line
Manual cleaning	Hand-removal	1. Northern Underwater Technical Services (New Zealand, www.divecom.co.nz/): Currently only hand-remove *Sabella* and recommend vessel owners slip for hull maintenance. They do prop-polishing using un-shrouded hydraulic and pneumatic buffers with regional council approval (no collection of waste). 2. Diving Services New Zealand (New Zealand), www.divingservicesnz.com): have carried out hand removal of *Didemnum*, *Styela* and *Sabella* from vessel hulls and other structures in the top of the South Island and Lyttelton.	1. None found 2. None found
	Hand-removal (with waste collection)	1. Scraper (150-mm broad knife – a plasterer's trowel) semi-encased with a shroud that is attached to an inhalant vacuum pipe (Wilson Underwater Services Ltd., New Zealand, http://www.wilsonunderwater.com) The diver-operator controls the vacuum pressure to vary the volume of water entrained through the system. In the past, this system was used with a petrol-powered pump to generate the vacuum at the scraper nozzle. The vacuumed water and de-fouled material was pumped through a coarse filter and then heated using a diesel heating unit to treat effluent (described in the heat treatment Section 4.3.1), before discharge back to sea. This unit was ineffective at the boot-top (air-water interface) because hydraulic pumps generally require a continuous supply of water for effective operation and any air entering the system can create an air-block and require the pump to be re-primed. WUS Ltd. now employ sewage vacuum trucks as the vacuum source for their manual system. The effluent is passed to the truck's reservoir tank and subsequently disposal of at an appropriate facility (e.g., to sewer). This allows constant vacuum force to be supplied to the system, and avoids returning effluent to the sea.	None found
Mechanical	Rotary brush / pad: diver hand tools (without waste collection)	1. Hydraulic unshrouded single-head "prop polisher" (Seahorse Diving Inc., USA, www.seahorsediving.com): silicon carbide brushes, 3M diamond disc pads. Does not appear to have a reclaim system. 2. Hydraulic unshrouded single-head MC-131 and MC-111 brush machines (Subsea Industries, Belgium, www.subind.net; Subsea Industries is a division of Hydrex, Belgium www.hydrex.be). Also supplied by Submarine Manufacturing & Products Limited (SMP LTD), UK (www.smp-ltd.co.uk): Rilsan, steel grass, steel wire, polypropylene brush heads. Does not appear to have a reclaim system. 3. UMC hydraulic unshrouded single-head MkII brush machine (UMC, UK, www.umc-int.com). Also supplied by Submarine Manufacturing & Products Limited (SMP LTD), UK (www.smp-ltd.co.uk): fine to coarse polishing pads. Does not appear to have a reclaim system. 4. Hydraulic unshrouded single-head AS16-3M9-PP prop polisher, single-head AS-T12 HB, AS16HB and AS18HB hull cleaner and prop polishers, twin-head AST-P-789 prop polisher and barnacle buster, hinged to allow conformation to hull shape (ArmadaHull, USA, www.armadahull.com/): silicon, polypropylene, nylon, flat wire steel, stainless steel brush heads; barnacle brush cutter blades; 3M marine	1. www.youtube.com/watch?v=yH9dsGrmztA 2. None found 3. None found 4. www.youtube.com/watch?v=MVfuHTBjjYQ

Category	Subcategory	Providers	Videos available on line
		polishing discs. Does not appear to have a reclaim system. 5. SMS "Propduster" hydraulic unshrouded single-head prop-polisher with abrasive pads (Sub Marine Services Ltd., UK, www.submarineservices.com). Does not appear to have a reclaim system. 6. Diving Services New Zealand (New Zealand), www.divingservicesnz.com): Use un-shrouded prop-polishers with polishing pads (no collection of waste) and have a larger, dive-held single-brush unit for cleaning hulls but have not used it recently.	5. None found 6. None found
	Rotary brush / pad: diver hand tools (with waste collection)	1. Hydraulic shrouded hand hydraulic scrapers that link to the Envirocart (Franmarine Underwater Services Pty Ltd., Australia, www.gageroadsdiving.com.au/) reclaim system. Two sizes, 40 mm and 100 mm blade-width scrapers are currently available. The system removes the biofouling in a contained system, with the waste pumped to the surface and processed through a multi-stage, high-speed filtration system that separates and contains all material removing material down to 5 µm. Filtrate is then treated with UV radiation for complete disinfection prior to discharge safely back into the ocean. 2. Hydraulic shrouded single-head brush cleaning unit that has the ability to contain fouling for use in propeller and niche area cleaning (UMC, UK, www.umc-int.com). Primarily created to limit the copper-based "fines" from the propeller surface entering the surrounding water, it has a companion filtration unit provided for removing particulates. This unit has only been used in Rotterdam to date due to local in-water cleaning restrictions. The company claims about 75% containment of removed fouling.	1. www.youtube.com/watch?v=dhxZnffAMaw 2. www.youtube.com/watch?v=M8xBZCD76ow (un-shrouded unit only)
	Rotary brush / pad: non-diver tools (with waste collection)	1. Hulltimo Smart battery-powered unshrouded single-head brush unit (normally operated from surface on flexible poles, but can be used by divers as well) (Hulltimo, France, www.hulltimo.com/en/): polyamide bristle head. Designed for small recreational vessels 5–12 m in length. Vacuum collection of waste into internal filter bag, but no specific information given on bag capacity or filter pore-size. 2. Scrubmarine system consists of a lightweight unshrouded single-head brush unit (mechanically driven) and a fish-eye camera, a telescopic handle, a high-output pump unit as well as flexible suction and discharge hoses and coarse and fine filter units. Designed for small recreational vessels. No specific detail is provided on filter capacity or filter pore size details are provided.	1. www.hulltimo.com 2. www.scrubmarine.com/scrub_uk/Movie.html
	Rotary brush / pad: cart (without waste collection)	1. Brush-Kart™ hydraulic unshrouded triple-head and mini Brush-Kart systems (Piccard Divers, Greece, www.piccard.gr). Also supplied/used by Phosmarine Equipment, France (www.phosmarine-brush-kart.com), Lufesa Divers, Peru (www.lufesa.com), Alldive, Malta (www.alldiveltd.com): steel wire, polypropylene brush heads. Does not appear to have a reclaim system. 2. Typhoon series (e.g., 312) (self-adjusting heads to mould to some changes in ship hull shape) hydraulic unshrouded triple-head brush cart and twin-head unshrouded brush machine (MC-212) (hinged unit to adjust to change in ship hull angle) (Subsea Industries, Belgium, www.subind.net; Subsea Industries is a division of	1. www.piccard.gr/brush-power-kart-models/ 2. www.youtube.com/watch?v=dvEjox2faCY

Category	Subcategory	Providers	Videos available on line
		Hydrex, Belgium www.hydrex.be). Also supplied by Submarine Manufacturing & Products Limited (SMP LTD), UK (www.smp-ltd.co.uk): Rilsan, steel grass, steel wire, and polypropylene brush heads. Do not have reclaim systems, although reclaim systems have been trialled by Hydrex. 3. Mini-Pamper hydraulic unshrouded two-head hull brush cart and twin-head brush unit (UMC, UK, www.umc-int.com). Also supplied by Submarine Manufacturing & Products Limited (SMP LTD), UK (www.smp-ltd.co.uk): polyester, silicon, stainless steel wire, twisted wire and coach bolt brushes. Plough attachment for heavy fouling for Mini-Pamper. Does not appear to have a reclaim system. 4. SeaRazzor super hydraulic unshrouded twin-head brush cart , twin-head (AS-T12 HBPP) (adjustable camber) hull cleaner and prop polisher, and twin-head (AS-T15 HB) (adjustable camber) hull cleaner (ArmadaHull, USA, www.armadahull.com): silicon, polypropylene, nylon, flat wire steel, stainless steel brush heads; barnacle brush cutter blades; 3M marine polishing discs. Do not appear to have reclaim systems. 5. Piranha hydraulic unshrouded twin-head brush cart (Sub Marine Services Ltd., UK, www.submarineservices.com). Does not appear to have a reclaim system. 6. PIRANHA hydraulic unshrouded brush system (La Mans Marine Engineering (LMME), Singapore, www.lamansmarine.com): Piranha Brush and brush kart, collectively known as The Piranha System, is designed to remove both hard and soft marine growth on flat-plate and large tubular surfaces, cleaning down to the paint coat or a shell base of less than 5mm thick. Designed for larger vessels and platforms. Consists of a subsea wheeled tractor unit driving a large triple-head brush unit, operated by a diver or ROV. The novel and critical aspect of the device is that each spring-loaded bristle or tine has the ability to rotate, freely and independently, 360° in either direction around the horizontal axis and at the same time independently move up and down through the vertical axis. Wing cutters are located on the circumference of the brush to reduce the height of excessive marine growth prior to its removal by the tines. Does not have a reclaim system, although LMME have indicated that would consider developing a reclaim system for the PIRANHA if there was sufficient market demand. 7. SCAMP® hydraulic unshrouded three-head brush cart (SCAMP, Gibraltar, www.scampnetwork.com). Does not appear to have a reclaim system. 8. Keelcrab PRO is a small diver-guided unshrouded cart (Aeffe Srl, Italy, http://www.keelcrab.com/en/product/keelcrab/keelcrab/). The cart has neutral hydrostatic balance; a central propeller enables the cart to stay attached to the keel while cleaning. The cart moves via rubber brushes operated by caterpillar tracks. For the removal of fouling there are two central brushes with nylon bristles of varying length and diameter. Does not appear to have a reclaim system.	3. www.youtube.com/watch?v=DlNlWTsqPHk 4. www.armadahull.com (for each unit) 5. None found 6. www.lamansmarine.com/ 7. None found 8. www.keelcrab.com/en/gallery/video/
	Rotary brush / pad: cart (with waste collection)	1. Diver Services NZ Ltd. system consisting of a Phosmarine™ hydraulic shrouded single-head brush unit fitted with vacuum reclaim system (Diver Services NZ Ltd., NZ). De-fouled material is pumped to a floating collection bag (filter sizes 30–	1. None found

Category	Subcategory	Providers	Videos available on line
		1200 µm). Tested in NZ on pre-fouled settlement plates and a vessel (Hopkins *et al*., 2008). Both this brush system and the NZDS Ltd. system described below (bullet point 2) proved effective (>80%) in removing low-to- moderate levels of fouling from experimental surfaces, however performance was generally poorer at removing more advanced levels of fouling. In particular, mature calcareous organisms were relatively resistant to the rotating brushes, with a high proportion remaining on plates following treatment. On average, >95% of de-fouled material was collected and retained by both systems, with less retention on surfaces that were curved or had more advanced levels of fouling present. The majority (typically >80%) of fouling not captured by the systems was crushed by the brushes (i.e. non-viable); however a wide range in types of viable organisms (e.g. barnacles, hydroids) were lost to the environment during the de-fouling trials. The trial on the fouled vessel revealed that, while the devices were capable of removing 100% of biofouling from the areas treated, unintentional detachment of fouling organisms by divers operating the devices and by equipment associated with the rotating brush was reasonably high. Furthermore, residual biosecurity risks were also likely to remain due to diver error (i.e. missed patches), persistent fouling remaining on treated surfaces (including microscopic life-stages) and the inaccessibility of niche areas to the brush systems. 2. New Zealand Diving & Salvage Ltd. system consisting of a road-sweeping hydraulic shrouded single-head brush unit fitted with vacuum reclaim system (NZ Diving & Salvage Ltd., NZ, www.nzds.co.nz). De-fouled material is pumped through a series of filters (1–400 µm) housed in a surface unit. Tested in NZ on pre-fouled settlement plates and a vessel (Hopkins *et al*., 2008). 3. New Zealand Diving & Salvage Ltd. system consisting of a hydraulic shrouded vacuum cutting head unit fitted with reclaim system (NZ Diving & Salvage Ltd., NZ, www.nzds.co.nz). De-fouled material is pumped through a series of filters (1–200 µm + mussel bag) housed in a surface unit. Tested in NZ on a barge extensively fouled with *Didemnum vexillum* (Coutts, 2002). The original vacuum cutting head was not effective at removing the *D. vexillum* colonies. With the cutting head removed, the diver-operated nozzle proved to be selective and efficient for removing a wide size range of *D. vexillum* colonies from the hull. A post-vacuuming quantitative survey revealed that the vacuuming operation removed an estimated 80% of the original *D. vexillum* wet biomass weight. The filtering plant used by NZDS illustrated that de-fouled material can be successfully filtered to 50 µm.	2. None found 3. None found
	Rotary brush / pad (non-contact): cart	1. Eco Hull Crawler hydraulic triple-head brush cart (UCS, Spain, www.ucspain.com). Older units can be retro-fitted with reclaim cups, whilst newer units have closed operation with 200-bar pumps in a combination with high volume hydraulic pumps, and reclaim filter system. No specific detail on filter system available. 2. Envirocart (Franmarine Underwater Services Pty Ltd., Australia, www.gageroadsdiving.com.au/) The primary underwater cleaning tool is a	1. None found 2. www.youtube.com/watch?v=dhxZnffAMaw

Category	Subcategory	Providers	Videos available on line
		hydraulic hull cleaning unit fitted with twin shrouded rotating discs that contour to flat, curved or convex hull surfaces. The disc's can be fitted with conventional brushes for glass or epoxy based coatings or a revolutionary new patented blade system which can remove marine biofouling without damaging the antifouling paint (silicone and copper oxide). When fitted with the non-contact system, a powerful vortex is created to clean primary and early secondary stage fouling from the hull surface without damaging the AFC. The system can be lowered into contact with the hull for heavier second stage macro biofouling. The system removes the biofouling in a contained system, with the waste pumped to the surface and processed through a multi-stage, high-speed filtration system that separates and contains all material removing material down to 5 µm. Filtrate is then treated with UV radiation for complete disinfection prior to discharge safely back into the ocean.	
	Rotary brush / pad: ROV	1. Hulltimo Pro battery-powered self-adjusting unshrouded twin-head brush crawler (uses cleaning suction force to adhere to hull) with video cameras (Hulltimo, France, www.hulltimo.com): polyamide bristle head. Designed for small recreational vessels 5–12 m in length. Vacuum collection of waste into internal filter bag, but no specific information given on bag capacity or filter pore-size. 2. Hull BUG (US Office of Naval Research / SeaRobotics, USA, www.onr.navy.mil/Media-Center/Fact-Sheets/Robotic-Hull-Bio-mimetic-Underwater-Grooming.aspx): autonomous, wheeled robot using brushes to clean and maintain hull surface. On-board sensors allow it to avoid obstacles and to detect areas of fouling (as chlorophyll fluorescence). Adheres to hull via suction created by a captive vortex within the cleaning head. Does not include a waste-capture system. 3. iKeelCrab and Keelcrab One are small semi-automatic devices (with video camera) for the cleaning of hulls (Aeffe Srl, Italy, http://www.keelcrab.com/en/product/keelcrab/keelcrab/). The robot has neutral hydrostatic balance; a central propeller enables the robot to stay attached to the keel while cleaning. The robot moves via rubber brushes operated by caterpillar tracks. For the removal of fouling there are two central brushes with nylon bristles of varying length and diameter. The iKeelCrab can be guided from smartphone or tablet, either with the Android or iOS operating system, while viewing on the screen what the robot sees underwater. Both robots can also be manoeuvred by a remote-control supplied together with the robot, which enables the video to stream in high definition. The underwater camera and the sensors for the recognition of the hull's limits allow a semi-automatic governance. Neither device includes a waste-capture system.	1. www.hulltimo.com/en 2. www.youtube.com/watch?v=yK5eb8bak5c 3. www.keelcrab.com/en/gallery/video/
	High-pressure water jet: hand tools	1. Magic Box enclosed water-jet hand tool with collection and filtration of waste (GRD Franmarine, Australia, www.gageroadsdiving.com.au): the Magic Box is placed over the area and injected with high-pressure water (5,000 psi), which is then forced in, under and around the object being cleaned. 2. Hydro-blasting tools (Subsea Global Solutions, USA, www.subseasolutions.com):	1. www.youtube.com/watch?v=dhxZnffAMaw 2. www.youtube.com/watch?v=3N8N1Jne5B0

Category	Subcategory	Providers	Videos available on line
		Prop-polishing water-jet tools. Does not appear to have a reclaim system. 3. Hydro-blasting tools (Sub Sea Services, Italy, www.subseaservices.it/): Water-jet tools. Does not appear to have a reclaim system.	3. None found
	High-pressure water jet: cart / ROV	1. Hullwiper HW02 ROV (Environtech, Norway, www.environtec.no): high-pressure seawater (no damage to antifouling claimed) and "all residues and pollutants are collected and disposed of" by waste collection and filtration unit connected to the ROV. Also supplied to GAC, Dubai (www.gac.com). 2. CleanROV (CleanHull, Norway, www.cleanhull.no): High-pressure seawater with capture and filtration. 3. UCS Direct Underwater Treatment System (UCS, Spain, www.ucspain.com): UCS ECO Crawler Hull Cleaner with water jet or multi-brush system, DUTS collects "all debris in a filter waste system" 4. ECOSubsea water-jet cleaning tools (ECOSubsea, Norway, www.ecosubsea.com/ (requires login)): Diver-operated water jet cleaning tool designed to collect 97.5% of material removed (this is based on capture of paint material only, from test-cleaning of freshly-painted test panel). 5. Magnetic Hull Crawler (Cybernetix, France, www.cybernetix.fr): MHC is a carrier-vehicle for various ship-maintenance equipment, including freshwater or seawater jet cleaning (1000bar) and has in the past been fitted with a vacuum tool connected to the surface to collect waste.	1. www.youtube.com/watch?v=9xf3AknxRrE 2. www.youtube.com/watch?v=TOrx4g13E5s www.youtube.com/watch?v=m7TSeD9FSO4 3. www.vimeo.com/68514671 4. www.youtube.com/watch?v=kK5BwXQJ_wY#t=72
	Cavitational jet (self-propelled, diver-operated carts and hand-held pistols) Uses microscopic steam / gas bubbles that collapse on contact with surface to produce very high pressure at the treatment point, "destroying" and removing organisms, rush and exfoliated paint.	1. CaviBlaster (CaviDyne LLC, USA, www.cavidyne.com): Uses ultrasonic cavitation to remove fouling (at 125 bar), delivered via hand pieces, diver-operated, wheeled vehicles, and can be attached to a ROV arm. Unclear whether organisms are killed or just disrupted. Does not appear to have a collection system for waste. Distributors in Western Australia and NSW. 2. Cavi-Jet (Limpieza Purotecnica S.A., Spain, www.cavi-jet.com): Uses ultrasonic cavitation to remove fouling (at 150 bar, with Cavi-Jet claiming 150,000 bar at point of treatment point), delivered via diver-operated, self-propelled units for flat or slightly-curved surfaces, hand-held Cavi-Jet pistols for niche areas, grinding and cleaning Cavi-Jet heads for prop polishing, etc. According to the company website, application does not damage underlying paint. Unclear whether the method kills the fouling organisms that it removes, rather than just breaking them up. Does not appear to have a collection system. 3. Roving Bat hybrid ROV / tracked unit (ECA Robotics, France, www.eca-robotics.com): Uses cavitational jets to clean. Does not appear to have a reclaim system.	1. www.youtube.com/watch?v=y_ERhQIsQJw 2. www.youtube.com/watch?v=bjlQUUVDVeM 3. www.youtube.com/watch?v=X0VJ0-vN4GI
Surface	Heat	1. Hull Surface Treatment (HST) System (T&C Marine, Australia, www.tcmarine.com.au): Uses heat shock (70°C) to kill growth on laminar-flow sides of hull. Applied via square applicator with soft skirt to prevent loss of material before treatment is complete. Material left on the hull sloughs off in transit. Designed to be applied regularly (e.g., twice per year) to keep fouling to a minimum.	1. www.youtube.com/watch?v=FoJYjD34v4U

Category	Subcategory	Providers	Videos available on line
		2. Heat-treatment of *Undaria* on hull of sunken trawler (NZ Diving and Salvage, New Zealand, www.nzds.co.nz/Default.aspx?page=2582): Plywood box with foam seals, heated by electrical elements, and attached to hull with magnets to treat flatter areas and Petrogen flame torch to treat niches, curved areas and heavily-fouled areas (in collaboration with MAF BNZ) / MPI). 3. Heat-treatment of biofouling on a tug (Wilson Underwater Services Ltd., New Zealand, http://www.wilsonunderwater.com) The treatment used divers to pump hot water over biofouling to kill the target species and other biofouling. Following treatment, the biofouling may be left in situ or removed with a scraper / vacuum system (see Section 4.1). Freshwater, rather than seawater, can be used to add an additional biocidal treatment. Water is heated on the deck of a tender vessel using a diesel heating system similar to those used in commercial steam cleaners. The continuous flow of low-pressure (e.g., 20 L min^{-1}) hot water is then pumped through a rubberised hose to a nozzle. The diver directs the water from the nozzle over the biofouling for the desired treatment time. Since the trial on the tug in December 2011, WUS Ltd. have increased the water temperature from 70°C to 110°C.	2. None found 3. None found
Shrouding	Floating dock and shrouds	1. FAB Dock floating dock with air-filled collar, designed to contain recreational vessels in marina berths or alongside wharves (Australia, www.fabdock.com). The back end of the dock is lowered to allow the boat to enter and then raised to enclose it. Water can be pumped out to minimise the volume of water inside the dock and prevent fouling. Small enough to be moved from location. 2. Bottom Liner Services (USA, www.bottomlinerservices.com). Similar to Fab Dock but intended for permanent installation at a berth. Rather than pumping water out of the dock, the manufacturer suggests that freshwater (10–15%) or swimming-pool chlorine be added to the water in the dock to prevent fouling growth. To prevent release of chlorine to the surrounding environment, the chlorine can either be neutralised or allowed to degrade naturally before the boat is taken out of the dock. 3. IMProtector (Australia, www.biofoulingsolutions.com.au) shrouding system, currently for vessels up to 18 m long and 5 m draft. Can be deployed on vessels at berth or anchor and by two people using a dinghy. Has been trialled for effectiveness and results indicate mortality of all fouling organisms within nine days with no added biocides or oxygen scavengers.	1. www.youtube.com/watch?v=FOuq0QXICfE 2. None found 3. None found
	Wrapping	1. Oceanwrap (New Zealand providers are Diving Services NZ Ltd) has been used to wrap vessels up to 30 m long during management of *Didemnum vexillum* in the Marlborough Sounds and a 113-m long naval frigate.	1. None found