Fisheries Occasional Publication No. 114, 2013

Report 1

In-water hull cleaning and filtration system: In-water cleaning trials

26-28 November 2012

Government of **Western Australia**
Department of **Fisheries**

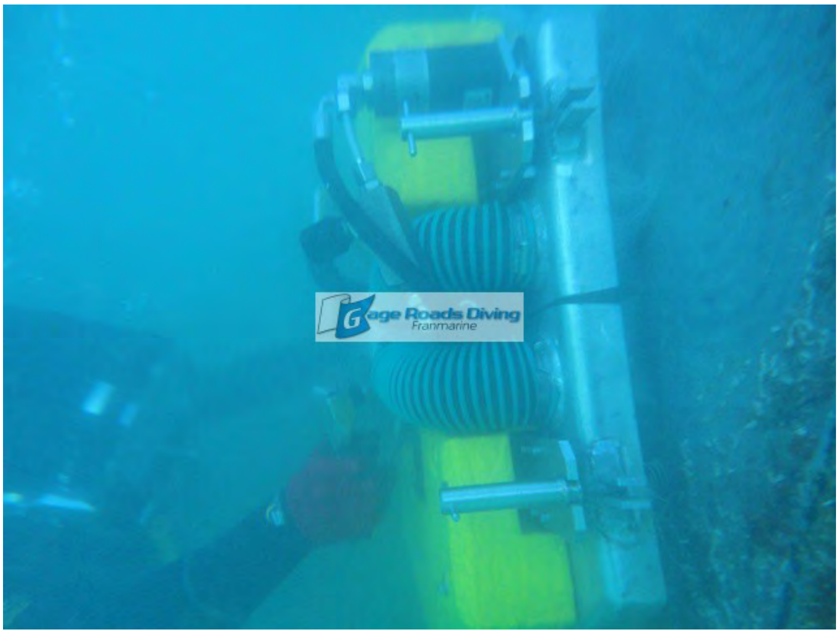
ESLINK
SERVICES

Fish for the future

Department of Fisheries
3rd floor SGIO Atrium
168 - 170 St Georges Terrace
PERTH WA 6000
Telephone: (08) 9482 7333
Facsimile: (08) 9482 7389
Website: www.fish.wa.gov.au
ABN: 55 689 771

ISSN: 1447 - 2058 ISBN: 978-1-921845-62-8

IN-WATER HULL CLEANING AND FILTRATION SYSTEM:
IN-WATER CLEANING TRIALS –
26-28 NOVEMBER 2012



Prepared for:

Franmarine Underwater Services
Australian Marine Complex
13 Possner Way
HENDERSON, WA, 6166

July 2013
Version 3.3

ES LINK SERVICES PTY LTD
ABN 76 088 414 037

2/233 Barker Street (PO Box 10) Castlemaine VIC 3450

T +61 (0)3 5470 5232 E info@eslinkservices.com.au W www.eslinkservices.com.au

IN-WATER HULL CLEANING AND FILTRATION SYSTEM: IN-WATER CLEANING TRIALS – 26-28 NOVEMBER 2012

Prepared for:

Franmarine Underwater Services
Australian Marine Complex
13 Possner Way
HENDERSON, WA, 6166

As part of trial outcome obligations set by

Department of Fisheries Western Australia

July 2013
Version 3.3

Prepared by:

John A Lewis

Principal Marine Consultant

ES Link Services Pty Ltd

Abbreviations

Abbreviation	Description
ANZECC	The Australian and New Zealand Environment Conservation Council
DoF	[Western Australia] Department of Fisheries
DoT	[Western Australia] Department of Transport
DPA	Dampier Port Authority
FPA	Fremantle Port Authority
FR	Foul Release Coating
FUS	Franmarine Underwater Services Pty Ltd
ICPAES	Inductively Coupled Atomic Emission Mass Spectometry
ICPMS	Inductively Coupled Plasma Mass Spectometry
NIMS	Non-Indigenous Marine Species
NIS	Non-Indigenous Species
USEPA	United States Environmental Protection Agency
UV	Ultra-Violet Light
WA	Western Australia

Table of Contents

EXECUTIVE SUMMARY

The settlement and growth of marine organisms (biofouling) on the underwater surfaces of vessels not only increases hull drag, and consequently fuel consumption and greenhouse gas emission, but also facilitates the translocation of potentially invasive marine species. Biofouling prevention or minimisation is most commonly achieved by the application of antifouling coatings, which prevent the settlement of marine organisms through the continuous release of a biocide or biocides at the paint surface but, often, biofouling can develop in unprotected or poorly protected niche areas, or on ineffective or depleted antifouling coating systems.

The most effective method for removal of biofouling from a vessel is to dry-dock or slip the vessel and physically remove the growth by high pressure water blasting, grit blasting and/or manual scraping, with all debris contained within the dock or around the vessel and disposed on-shore. However, dry-docking or slipping is costly and not always feasible and in these circumstances, rather than requiring the vessel to depart and move the problem elsewhere, methods for in-water containment and treatment or removal and capture would provide a useful tool to counter the biosecurity risk. Uncontrolled in-water cleaning may increase the risk of incursion by stimulating the release of reproductive propagules, or plant and animal fragments capable of regeneration. More generally, in-water cleaning can release chemical and biological contaminants into the local environment, and environmental protection is best achieved if these wastes can be contained and captured. No proven technology is yet on the market to satisfactorily achieve this aim (Floerl et al 2010).

In response to this identified need, in mid-2011, the WA Department of Fisheries issued a request for a service provider to develop a system for trials for the in-water treatment and removal of marine biofouling by vessel encapsulation and cleaning technologies to kill and remove biofouling from large (40m+) vessels.

Franmarine Underwater Services Pty Ltd had already designed and built a prototype lightweight, portable hull cleaning system deemed capable of meeting this requirement and the prototype was assessed in 3 trials in Perth on 26-28 November 2012.

Three separate trials were undertaken to assess the performance of the Franmarine in-water cleaning system. The first trial was to demonstrate the level of biofouling removal, extent of capture, and containment of debris > 50 μm in diameter from a heavily fouled, non-toxic underwater surface; the second to determine the occurrence of any physical damage to a biocide-free, silicone foul-release coating from the cleaning cart; and the third to demonstrate the level of biofouling removal, the extent of capture and containment of debris > 50 µm in diameter, and the control and containment of released copper during cleaning of a vessel hull painted with a copper-based antifouling coating.

The first trial was undertaken on the floating dry-dock, *Yargan* at the Australian Marine Complex, Henderson, WA, on 26 November 2012. The underwater surfaces of the *Yargan* were painted with a high performance epoxy protective coating, but no antifouling. In this trial the *Envirocart* in-water cleaning system was demonstrated to be effective in removing established primary and secondary biofouling from the flat vertical sides and bottom of the dock, capturing all biological waste removed from the hull, and filtering out and capturing all biological debris and other matter > 50 µm in diameter. The *Envirocart* did not completely remove biofouling from alongside hull irregularities, such as weld lines, nor completely remove all calcareous biofouling baseplates. However, these areas could be cleaned by follow-up cleaning with the system's hand tools.

The second trial was undertaken on a test panel coated in a silicone foul-release coating that had been immersed for 10 months at the Austal Ships facility at Henderson, WA, on 27 November 2012. In a previous trial, the *Envirocart* had caused some unacceptable scuffing of the coating surface. In this trial all biofouling was effectively removed from the silicone surface, but there was again some mechanical damage to the surface. Scratches were caused by the hard plastic jockey wheel jamming and dragging across the surface, and scuffing and light radial scratching caused by one of the cleaning discs not being securely attached. No damage was caused by the other, securely attached, cleaning disc. Both of these problems appear easily rectifiable, but a further trial is necessary after the repairs and modifications to demonstrate that the system is safe to use on foul-release coatings.

The third trial was undertaken on the hull of the Svitzer tug *Wambiri* in Fremantle Port on 28 November 2012. The underwater hull of the *Wambiri* was painted with a copper-based antifouling coating. In addition to the cleaning trials, water samples were taken for chemical analysis from close to the hull before, during and after the trial to determine if copper was released during the clean, and from the treatment system effluent. The *Envirocart*, "magic box" and hand cleaning tools were all demonstrated in this trial to effectively remove, capture and contain biofouling growth from hull and other underwater surfaces and structures.

Difficulties encountered in securing the “magic box” to the hull, and in capturing all heavy fouling when hand scraping are considered easily rectified by minor design modifications.

Analysis of the water samples showed no suggestion of any elevation of copper or other heavy metals in the water column adjacent to the vessel during or after the cleaning trial. Significant levels of copper were measured in samples of the effluent from the biological treatment system, but with levels much lower when using the blade discs then the brushes. Estimation of the total copper that would be entrained in the effluent during a full clean of a hull of a similar size to the *Wambiri* indicate that, if discharged, it would amount to less than that passively released in one day from the antifouling coating of a commercial ship berthed in the port.

Overall, these trials of the Franmarine in-water hull cleaning and filtration system demonstrated the system to be effective in removing, capturing and containing biofouling and other debris > 50 μm in diameter, from vessel surfaces coated with either hard, non-biocidal protective coatings or biocidal antifouling coatings. For the latter, chemical contamination assessment indicated that copper-containing effluent from the cleaning was at a level unlikely to cause harm if discharged directly into adjacent water body.

1 INTRODUCTION

The settlement and growth of marine organisms on the underwater surfaces of vessels increases drag, and consequently fuel consumption and greenhouse gas emissions, and can facilitate the translocation of potentially invasive marine species. Biofouling prevention or minimisation is most commonly achieved by the application of antifouling coatings, which prevent the settlement of biofouling organisms through the continuous release of a biocide or biocides at the paint surface. In recent times, non-toxic foul release coatings, which do not prevent but minimise the strength of adhesion of biofouling, and hard, scrubbable coatings that require regular cleaning to prevent biofouling accretion, have also been adopted as alternatives to biocidal antifouling coatings.

In-water cleaning of the immersed hulls of vessels can be warranted to:

- Remove slime and biofouling to improve hull and fuel efficiency;
- Remove biofouling growth after periods of vessel lay-up or low activity;
- Maintain foul release or scrubbable coatings; and
- Contain and remove potentially invasive marine species.

Invasive non-indigenous species (NIS), along with habitat destruction, have been considered to be the leading cause of species extinctions and biodiversity loss worldwide. Within the marine realm, non-indigenous marine species (NIMS) have been cited as one of the top five threats to marine ecosystem function and biodiversity. A significant, and possibly the most significant, ongoing vector for the translocation of NIMS across natural marine biogeographic boundaries is now acknowledged to be biofouling of vessel hulls. Australia’s evolutionary isolation and high marine diversity and endemism has placed it at risk of invasion by exotic marine species, and invasive marine species can create environmental, economic, human health and socio-cultural impacts. The eradication of NIMS from the natural environment, even on first detection, is rarely possible and the most effective strategy is to proactively minimise the risk of NIMS translocation through the minimisation and management of vessel biofouling. However, should a NIMS considered to present a new risk be detected on a vessel on, or soon after arrival in a location, containment of that individual or population on the vessel could prevent the release of reproductive propagules that could colonise the local environment.

The most effective method for removal of biofouling from a vessel is to dry-dock or slip the vessel and physically remove the growth by high pressure water blasting, grit blasting and/or manual scraping, with all debris contained within the dock or around the vessel and disposed on-shore. However, dry-docking or slipping is not always feasible and in these circumstances, rather than requiring the vessel to depart and move the problem elsewhere, methods for in-water containment and treatment or removal and capture would provide a useful tool to counter the biosecurity risk. Uncontrolled in-water cleaning may increase the risk of incursion by stimulating the release of reproductive propagules, or plant and animal fragments capable of regeneration. More generally, in-water cleaning can release chemical and biological contaminants into the local environment, and environmental protection is best achieved if these wastes can be contained and captured. No proven technology is yet on the market to satisfactorily achieve this aim (Floerl et al. 2010).

In mid-2011, the WA Department of Fisheries issued a request for a service provider to develop a system for trials for the in-water treatment and removal of marine biofouling by vessel encapsulation and cleaning technologies to kill and remove biofouling from large (40m+) vessels. The system would be required to stand alone and meet all government requirements including, but not limited to, those imposed by the Department of Transport (DoT) and the Dampier Port Authority (DPA).

Franmarine Underwater Services Pty Ltd (Franmarine) has designed and built a lightweight, portable hull cleaning system that removes and captures marine growth from a vessel or other underwater surface through a fully enclosed suction system. Franmarine was successful in proposing this system in response to the DoF request, and was funded to proceed with trials. Initial trials of the prototype system demonstrated considerable promise, and warranted further, more detailed testing and trials to demonstrate that the system could meet the DoF requirement.

This report describes practical trials of the Franmarine in-water cleaning system in Perth waters on 26, 27 and 28 November 2012.

2 THE SYSTEM

2.1 Overview

The primary tool for the removal of marine growth from flat or curved underwater surfaces is the "*Envirocart*"; a diver-steered, hydraulically-powered unit with twin rotating discs that can be fitted with either brushes or blades. For less regular surfaces, shrouded hand tools, and a containment box have been designed. Each cleaning tool has a suction shroud that connects separately to the central, fully enclosed suction system through which debris is pumped onto the support vessel or wharf for treatment.

Extracted water and debris is the processed through a multi-staged, modular filtration and treatment systems where biofouling debris and particles are removed, then the filtrate passed through an automated UV disinfection unit.

2.2 The Cleaning System

2.2.1 MkII Envirocart

The *MkII Envirocart* has two counter-rotating discs to which 300 mm diameter brushes or bladed discs are attached (Figure 2.1). The discs are hydraulically driven, and the total width of clean in one pass is 700 mm. The chassis and drive systems both have scissor actions that enable the cart to clean flat and curved surfaces including, for example, the turn of the bilge. The lower rim of the cart body is fringed by a shroud of dense, flexible bristles that act to contain debris within the area of suction, and there are two forward wheels and a rear jockey wheel for movement and manoeuvrability across the surface to be cleaned. Suction of debris is generated by the submersible trash pump and hydrodynamic vortices generated by the brushes, and water and material is drawn through ports to a central and two lateral suction lines which lead into the 4" hose to the trash pump (Figures 2.2, 2.3). A foam float is fitted to the upper side of the cart to provide neutral buoyancy of the unit underwater (Figure 2.3).

Different cleaning discs and wheels can be fitted to the cart for different cleaning tasks. These include:

- Combination steel and nylon bristle brushes for heavy fouling removal on scrubbable, biocide-free coatings or other hard substrates (Figure 2.1);
- All nylon bristles for biocidal conventional or copolymer antifouling coatings; and
- 45° nylon blades for contactless cleaning (Figure 2.4).

The *Envirocart* has a top speed of 1.5 knots and has the capability to clean 1000 m^2 per 6 hour day.

2.2.2 Niche Cleaning

The brush cart cannot clean irregular hull surfaces, invaginations or protrusions of the hull, and hull appendages. For the cleaning of these, the trash pump is fitted with an additional 2" hose for attachment of interchangeable niche cleaning tools. Each tool has a suction shroud that connects separately to the central suction system which allows multiple, concurrent cleaning tasks.

Hand- Scrapers with Shroud

For small areas, such as along weld lines and bilge keels, shrouded hand scrapers have been designed. Two sizes, 40 mm and 100 mm blade width scrapers are currently available (Figure 2.5).

Magic Box

The "magic box" is a transparent plastic box that can be centrally hooked onto a removable magnetic hull attachment or to an anode or other hull appendage. The box then seals onto the hull when suction is applied from the 2" suction hose to the trash pump. Access ports in the box walls allow a high pressure (5000 psi) water lance to be inserted to clean biofouling from the enclosed surfaces.

Submersible Hydraulic Trash Pump

The capacity of suction system has been demonstrated in trials to be 3000 l/min of contaminated water.

2.3 Filtration, Treatment & Containment

2.3.1 First Stage Filtration

The trash pump lifts water and debris through a 4” hose to the first stage filtration system. This unit comprises a feed box which allows a consistent flow of feed slurry onto an inclined, static woven mesh screen (the *Baleen Filter* ®) (Figure 2.6). Mesh size on the prototype unit is 50 µm, although finer mesh could potentially be used. Any oversize or near-size particles (including viscous emulsion, if present) are retained on the screen surface and the slurry filtrate passes through the mesh screen by gravity. The oversize material is fluidised from the screen surface by a low volume, high pressure water spray bar located below the surface of the screen and perpendicular to it (Figure 2.7). Concurrently, a similar spray bar located above the screen surface, and at a slightly forward orientation, flushes the fluidised bed of oversize material to the discharge end of the screen for collection in a disposable bin bag.

The connected top and bottom spray bars travel down the screen in a pneumatically-driven carriage system. When the carriage reaches the lower limit of travel at the lower end of the screen, the spray water is cut off and the carriage returns to the feed end of the screen for the next cleaning cycle.

The entire unit is constructed of either stainless or duplex steel.

2.3.2 Second Stage Filtration

Filtrate from the first stage filtration is further filtered by pumping it through a series of four back-flushable filter units that contain high volume, interchangeable, cartridge filters (3M^{TM} High Flow 40” filter cartridges, 25 µm media grade) capable of removing particulate material greater in size than 2 – 5 µm (Figure 2.8). 3M^{TM} internal laboratory testing determined the removal efficiency of these cartridges to be 98.93% for 3-5 µm particles (A Ng, 3M Purification Pty Ltd, personal communication 13 March 2012). The filters are regularly back-flushed when resistance increases (in practice about every 25 min), with the back-flushed water discharged back into the solids bin, drained, then recycled back through the filtration process. Back-flushing and cleaning re-generates 60% of a filter’s efficiency, but ultimately the cartridges reach a maximum operating back pressure and need to be replaced. Filter units in the series can be individually isolated for the filter change-out, which can be achieved in less than 10 minutes[1].

2.3.3 UV Disinfection

After filtration through both first and second stage filtration, the filtrate is disinfected by passing through an automated UV chamber (Figure 2.8). Filtered and treated water is then released for discharge, or can be contained and pumped into tankers for onshore disposal.

UV treatment is one of the technologies commonly utilised in IMO-approved ballast water treatment systems for the disinfection stage after solid-liquid separation, and close to one third of the available treatment systems use UV disinfection (Lloyd's Register Group, 2012). Lloyd's report that physical disinfection by UV irradiation is a well-established technology, is used extensively in municipal and industrial water treatment applications, and is effective against a wide range of micro-organisms. UV light denatures the DNA of microorganisms, which prevents them from reproducing (Lloyd's Register Group, 2012).

2.3.4 Waste Disposal

Waste material from filtration is captured in 1 tonne pallet bags for on-shore disposal in accord with local government or other regulatory requirements. Should it be required, liquid effluent van be contained and pumped into tankers for onshore disposal, also in accord with local government or other regulatory requirements.

---

[1] 3M™ High Flow Filtration Systems [Product information]. 3M Purification Pty Limited, Blacktown NSW. Issued July 2012.

Figure 2.1 Upper and lower views of the *MkII Envirocart*

Figure 2.2 Under surface of cart showing suction ports (white arrows) and shroud (red arrow).

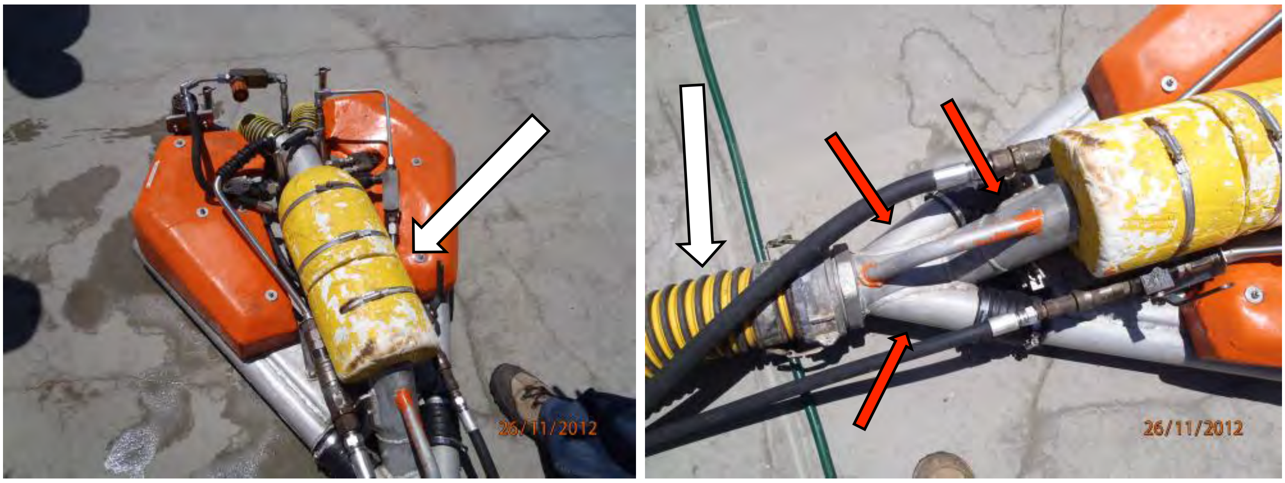


Figure 2.3 Upper surface of cart showing, left, buoyancy float and, right, suction outlets (red arrows) and hose (white arrow).

Figure 2.4 Cleaning heads with non-contact nylon blades.

Figure 2.5 40 mm (left) and 100 mm (right) shrouded hand-cleaning blades.

Figure 2.6 First stage filtration: filter screen

26/11/2012

26/11/2012

Figure 2.7 First stage filtration: upper and lower spray bars

26/11/2012

26/11/2012

Figure 2.8 Second stage filtration assembly (left) and UV treatment unit (right).

3 THE DOF REQUIREMENT

The DoF request specified that the successful Respondent must develop a system to conduct trials that could evaluate and demonstrate the costs and benefits of using in-water encapsulation for large marine vessels in comparison to conventional biofouling practices used to prevent the introduction of invasive marine species to Western Australian waters. The requirement was for the services of an operational system to undertake trials for the in-water treatment and removal of marine biofouling. The system should be able to stand alone and should meet all government requirements, including but not limited to those imposed by the DoT and the DPA.

The specification was for the development of a trial system that**:**

- Is capable of safely and securely encapsulating and treating (killing and removing bio-foul organisms in a timely manner) a range of vessels types and sizes;
- Is suitable for 40m vessels in the trial and that can be scaled to accommodate larger vessels (55 m long);
- Is deployed in the Dampier region to service including but not be limited to, oil and gas industry vessels;
- Tests a range of chemical and/or alternate (e.g. anoxia, freshwater) treatments to neutralise marine bio-fouling;
- Includes a cost-benefit analysis that evaluates the efficacy and suitability (environmental impact, cost, accessibility) of each treatment tested;
- Contains all treatment chemicals and bio-fouling organisms removed from vessel with zero to minimal discharge and/or impact to the surrounding marine environment;
- Safely captures and removes all bio-fouling organisms and residue for analysis and safe disposal;
- Uses novel techniques such as digital video and/or sonar imaging to provide a record of the extent of biofouling on each vessel;
- Includes methods that are capable of killing and removing bio-foulers from all areas on a vessel including the hull and vessel bottom, plus niche areas such as propellers, propeller shafts and sea chest grates;
- Allows the DoF, or their representative, to conduct in-situ research to evaluate the efficacy of the system and treatment methods used to kill and capture marine bio-fouling organisms (approximately within one month of development); and

- Includes practical considerations of using these technologies such as start-up and running costs, accessibility and Occupational Health and Safety issues.

4 TRIAL 1 – MECHANICALLY-RESISTANT, BIOCIDE-FREE COATING

4.1 Aim

To demonstrate the level of, and quantify, biofouling removal; the extent of capture, and containment, of debris >50 µm in diameter.

4.2 Test Surface

Trial 1 was undertaken on floating dry-dock *Yargan*, located at the Australian Marine Complex, Henderson, WA (Figure 4.1). *Yargan* is constructed of steel and underwater surfaces are painted with a high performance anti-corrosive marine paint system. The current top coat, applied in November 2007, is a two component epoxy coating, *PPG Sigmashield 420*. No antifouling coating, either biocidal or biocide-free, was applied.

4.3 Method

The *Yargan* trials were conducted on 26 November 2012, with the filtration and treatment system located on the cross-wharf adjacent to the dry-dock (Figure 4.1). The *Envirocart* was fitted with brushes having half firm nylon, and half steel bristles. The second stage filtration system was not connected for this trial, so filtrate from the 50 µm filter passed directly into the UV unit and was then discharged.

Two areas were cleaned: and an area on the vertical side of the dock, from chine to waterline, and an area on the flat bottom. Digital still photographs of these areas were taken prior and subsequent to the clean. The operator of the *Envirocart* wore a helmet-mounted video camera, and video during the clean was monitored live dock-side, and recorded.

4.4 Observations & Results

Prior to cleaning, the vertical underwater sides of the *Yargan* were approximately 75 – 100% covered by secondary biofouling comprising predominantly filamentous hydroids and macroalgae (Figure 4.2). Some scattered juvenile mytilid mussels had settled on to this filamentous growth. In contrast, the flat bottom was heavily colonised by a diverse and well-developed community of secondary foulers including sponges, solitary and colonial ascidians, and serpulid tubeworms, and on this there were some attached scallops (Figure 4.3).

During the clean, the biological debris removed from the hull was clearly evident on the first stage filter screen and being washed into the waste bag (Figure 4.4). Most of the growth on the filter was crushed or mashed, but many small mussels came through unbroken. Some larger bivalves and small fish passed through the pump and onto the screen intact and alive (Figure 4.5). The only indication of organic matter passing through the filtration process was the formation of a scum and foam on the surface of the discharge tank and around the discharged water plume (Figure 4.6). This was green when green macroalgae were being cleaned from the surface and appeared to be either spores or cell contents, and brown at other times suggesting fine silt or clay particles or disassociated organic matter (Figure 4.6).

Microscopic examination of material collected from the scum in the discharge tank found predominantly disaggregated organic matter, with a few recognisable diatoms. No particulates greater than 12.5 μm were seen, and particles approaching this size were uncommon.

After cleaning, smooth areas of hull plate were mostly visibly free of biofouling on both the vertical sides (Figure 4.7) and flat bottom (Figure 4.8). Biofouling encrustation did persist alongside hull irregularities, such as weld-lines, but on the flat hull plate only some scattered and isolated calcareous baseplate scars of oysters and tubeworms remained (Figure 4.9). The only mechanical damage to the coating from the cleaning was light scuffing from contact of the brushes. These would not compromise coating life or performance.

No biological debris was observed to escape from around the *Envirocart*. An experiment was undertaken to determine the area of suction and containment of water and debris around the perimeter of the cart. Blue food dye was squirted into the water in a line extending out from the shroud. The distance to which water and dye was drawn under the shroud was approximately 150 mm.

4.5 Discussion

The *Envirocart* in-water cleaning system was effective in:

1. Removing established primary and secondary biofouling from the flat vertical sides and bottom of the *Yargan*;
2. Capturing all biological waste removed from the hull; and
3. Filtering out and capturing all biological debris and other matter > 50 μm in diameter.

The brush cart system did not:

1. Remove biofouling from alongside hull irregularities, such as weld lines; and
2. Completely remove all calcareous baseplates.

However, these areas could readily be cleaned using the manual niche cleaning tools.

In addition, fine organic material passing through the system was lifted to the surface of the water by entrained fine bubbles in the discharge tank and formed a surface scum. Some of this was discharged and formed a small plume in the seawater around the discharge stream.

Figure 4.1 Dry-dock *Yargan* (left), and first stage filtration unit (right).

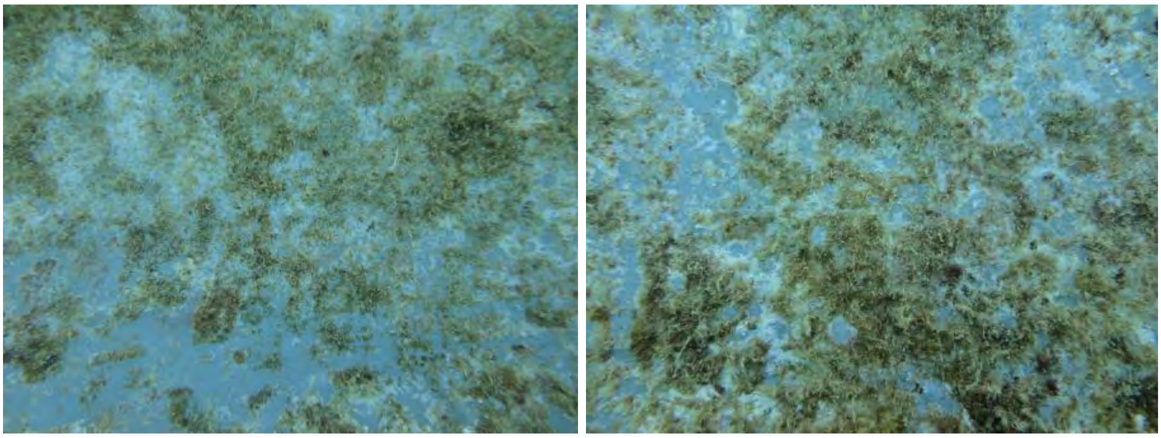


Figure 4.2 Biofouling on the *Yargan* vertical sides before cleaning.

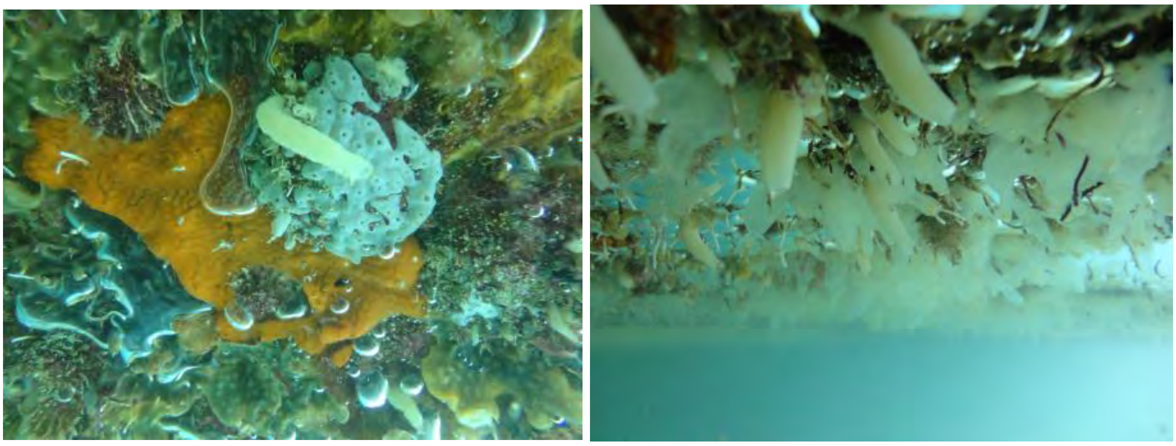


Figure 4.3 Biofouling on the *Yargan* flat bottom before cleaning.

Figure 4.4 Debris greater than 50 µm accumulating on the baleen screen (left) and washed into the waste bag (right).

Figure 4.5 Captured debris, including juvenile mytilid mussels (arrowed) and an intact scallop (right).

Figure 4.6 Organic scum derived from the filtrate in the discharge tank (left) and beside the *Yargan* (right).

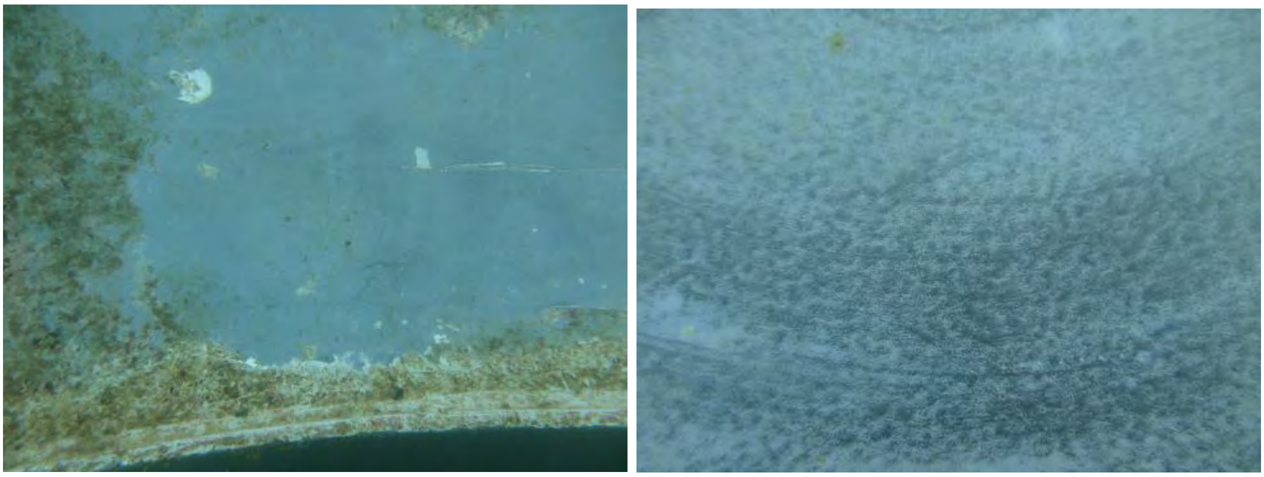


Figure 4.7 Cleaned area on the vertical side.

Figure 4.8 Residual oyster base (left) and paint blistering defects (right) on the vertical side.

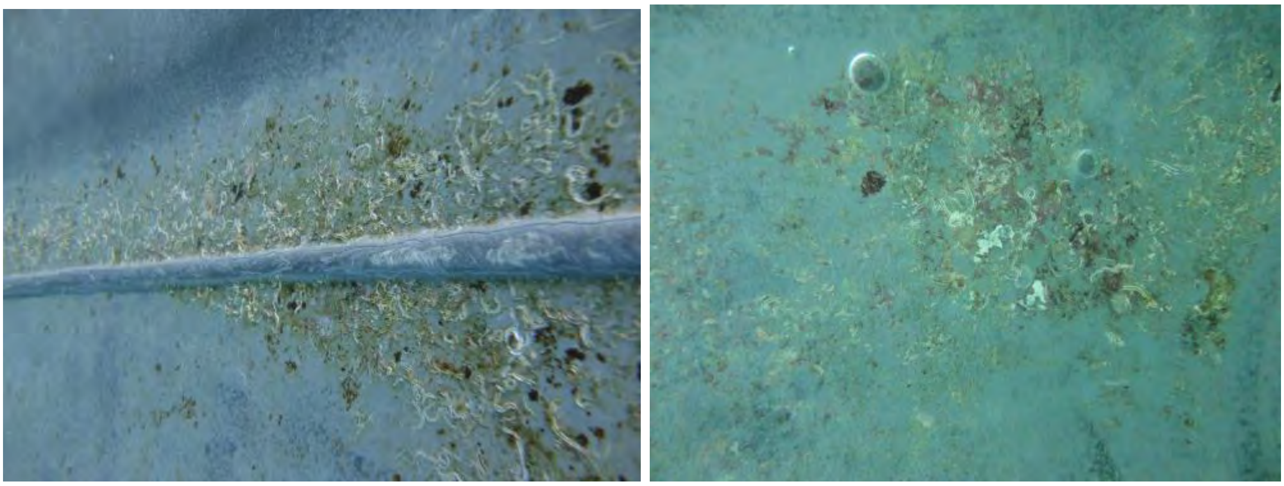


Figure 4.9 Fouling along weld-line after *Envirocart* cleaning (left) of the flat bottom, and some residual calcareous bases (right)

5 TRIAL 2 – SILICONE, FOUL-RELEASE COATING

5.1 Aim

To determine any physical damage to biocide-free, silicone foul-release coating caused by the cleaning cart.

5.2 Test Surface

Cleaning trials were undertaken on a 2000 x 1000 mm aluminium plate painted with a full silicone foul release (FR) system that had been immersed for 10 months from the edge of the cross wharf at the Austal Ships facility at Henderson, WA. The FR coating applied was *International Intersleek 425* (red)*,* over a tie-coat (*Intersleek 386*) and epoxy primer (*Intershield 300).*

The painted panel was first immersed on January 2012. Initial cleaning trials of the *MkII Envirocart* fitted with bladed cleaning discs were conducted on half of the panel on 20 Nov 2012. Some scuffing of the surface was observed, due to the blades touching the coating surface, so a repeat trial was warranted after modifications to the cart to prevent contact.

5.3 Method

The trial was conducted with the test plate in its suspended position adjacent to the wharf. The cart was positioned on the lower half of the panel with no part of the chassis overhanging the edge of the panel. The clean was conducted by propelling the cart upwards on the long axis of the panel. The first pass was with the left-hand brush over the previously cleaned area of the panel and the right-hand brush on the uncleaned area. After the pass, the panel was recovered, inspected, and returned for a second cleaning pass. On the second pass the left hand brush was positioned over the area cleaned in the first pass, and the right hand brush over the uncleaned portion near the right panel edge.

5.4 Observations & Results

Prior to cleaning, the previously uncleaned surface of the panel was approximately 50 to 80% covered by calcareous serpulid and spirorbid tubeworms (Figures 5.1, 5.2). Tufts of fine filamentous algae, possibly brown ectocarps, grew between and over the tubeworms. Scattered colonies of compound ascidians (botryllid & didemnid sp(p).), a cluster of fanworms (*Sabella*), and some encrusting bryozoans were also present (Figure 5.1). The bladed discs easily removed this biofouling with a single pass, apart from a thin strip between the discs (Figure 5.3). On a hull surface, this residual growth could easily be removed by overlapping subsequent passes, or running the cart transversely across the surface.

The cart passes in this trial caused two types of damage to the FR coating: elongate scratching of the silicone coating under the mid-line of the chassis (Figure 5.4), and light radial scratching and scuffing of the surface by the left-hand disc (Figure 5.5). The former was determined to be due to the hard plastic jockey wheel either jamming or dragging across the coating surface as the cart moved forward or, less likely, shell-growth being caught on around the jockey wheel and scoured across the paint.

The second type of damage was due to the blades on the left hand disc touching the coating surface. Although the blades had been set to ensure they did not do this, it was found that the bolts holding the left-hand blade disc had loosened causing the disc to wobble and touch the surface. On inspection, blades on this disc had traces of paint on their inner edge. The track under the right-hand disc showed no sign of scratching or scuffing, and the surface was completely free of any visible micro- or macro-fouling.

5.5 Discussion

This trial demonstrated that, if correctly set, the non-contact bladed discs could remove all biofouling from a silicone FR coating without causing damage to the coating surface. However, the physical damage caused to the coating surface by the jockey wheel and a loose cleaning disc needs to be addressed before the cleaning system could be used on a silicone FR painted vessel hull. Scratching of the type seen in this panel trial, if widespread across a ship hull, would degrade the coating system in a way which would facilitate settlement and strong adhesion of macrofouling organisms.

The loosening of the disc was determined to be an operator error that could be addressed by closer scrutiny to the disc set-up before deployment. The problematic jockey wheel requires redesign of the wheel shape or material to prevent jamming and/or dragging on silicone elastomer coatings.

Figure 5.1 FR coated test plate prior to cleaning.

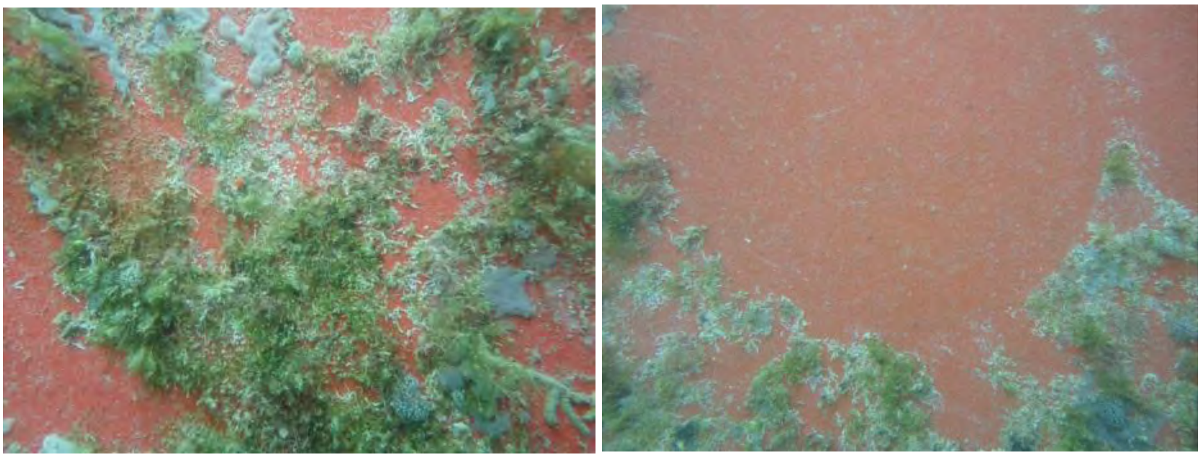


Figure 5.2 FR coated test plate prior to cleaning. Left image shows area cleaned in previous trial.

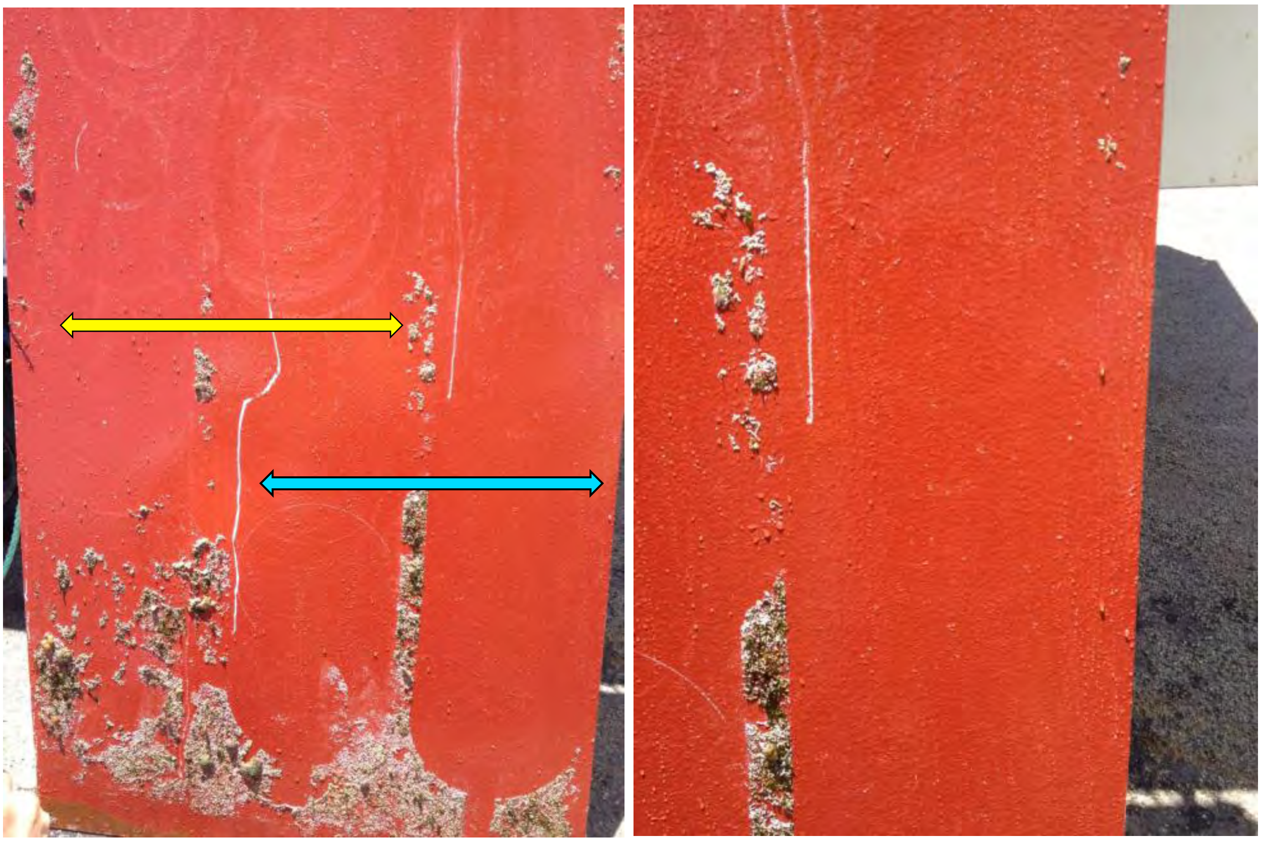


Figure 5.3 Test panel after the first (yellow) and second (blue) cart passes, and the cleaned and undamaged surface from under the second pass of the right hand disc.

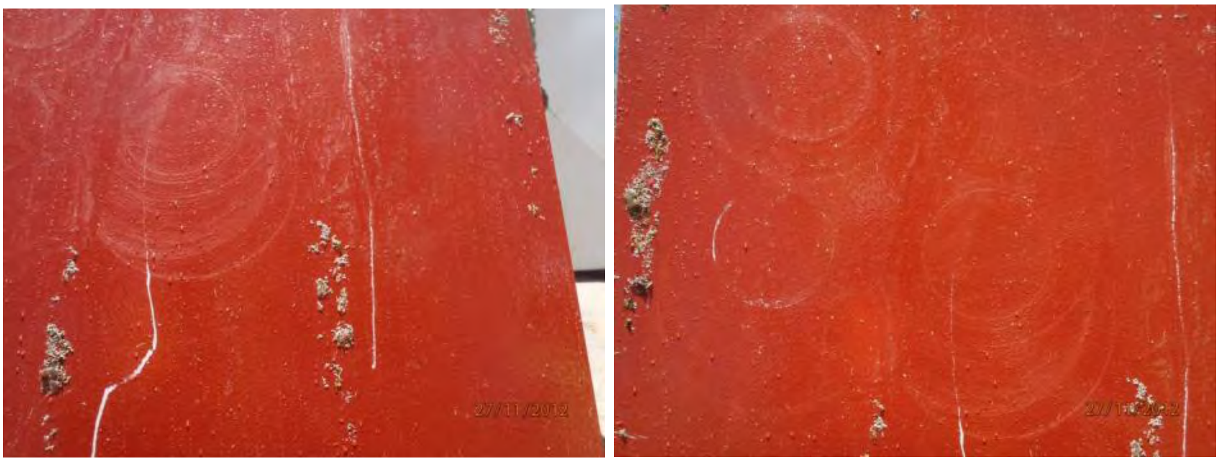


Figure 5.4 Scuffing of the coating surface caused by the blades touching the surface.

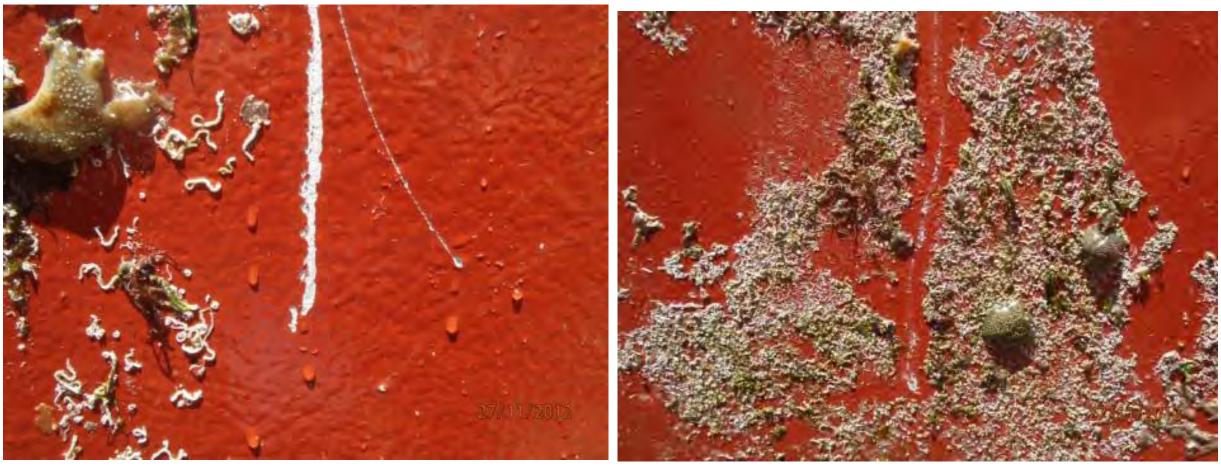


Figure 5.5 Scratches on the coating surface caused by the dragging jockey wheel.

6 TRIAL 3 – BIOCIDAL COATING

6.1 Aim

To demonstrate the level of, and quantify, biofouling removal, the extent of capture and containment of debris > 50 µm in diameter on a biocidal coating, and the control and containment of released copper to be within local water quality discharge limits or other requirements.

6.2 Test Surface

In addition to the requirements of the original DoF request (Section 3) and requirements of the FUS Environmental Management Plan, DoF added requirements for this trial that the trial vessel must be self-propelled, have sea chests and other niche areas, be 30+ m in length, and have an antifouling coating less than 3 years old. The Svitzer tug *MT Wambiri* met these requirements and approval gained to use this as the test vessel (Figure 6.1). Approval for the trial was also granted by the FPA.

The antifouling coating on the *Wambiri* is Sigma *Ecofleet 290* which was applied during a dry-docking of the vessel 13 months earlier. *Ecofleet 290* is a TBT-free self-polishing antifouling coating that contains the biocides cuprous oxide and diuron. The hull of the *Wambiri* is fitted with sacrificial cathodic protection (CP) anodes, and has sea chests and other niches prone to biofouling accumulation.

6.3 Method

6.3.1 Biofouling Removal & Capture

Cleaning trials to remove growth from the hull were undertaken with the *Envirocart* fitted firstly with bladed discs, and then brushes with soft nylon bristles. Suction water and cleaning debris was passed through all treatment stages: first stage filtration, second stage filtration, and UV treatment. However, additionally, all liquid filtrate was contained and pumped into tanker trucks, as required for this trial by the Fremantle Port Authority (FPA). The clean durations were 15 min with the bladed discs, and 15 min with the brush.

A trial of the “magic box” was undertaken by positioning the box over a CP anode on the *Wambiri* hull. When sealed in position over the anode, a high pressure (3000 psi) water lance was inserted through the access ports in the box to jet biofouling form on and around the anode.

The final trial of this set assessed the use of the 100 mm shrouded hand scraper. Rather than demonstrating this on the hull, which had only primary biofouling, the scraper was used to remove well developed biofouling from a wharf pile adjacent to the *Wambiri.*

6.3.2 Chemical Contamination Assessment

Prior to, and after the hull clean, water samples were collected by the divers at pre-planned locations around, and distances out from the hull to primarily detect any elevation of seawater copper concentrations from the hull cleaning. The sampling procedure, collection and management was overseen by DoF personnel on-site[2].

Water samples (n=204) were collected by divers at 2 depths (0.5 m and 2 m) at three locations along the vessel: stern (0.5 m), midship (2 m) and bow (5 m). Five replicates were taken at each depth and vessel location before, during and after cleaning. Due to weather conditions, samples were taken at three different areas rather than different distances of the vessel. An additional 24 samples were also taken from the post-UV treatment outflow reservoir during cleaning: 14 when a bladed disc was fitted and 10 with a brush disc fitted.

After collection, samples were stored in ice and transported to the WA Chem Centre for analysis. Prior to analysis, 500 mL of each sample was filtered through a 0.45 µm filter and the quantity of analyte retained on the filter, and the concentration of analyte in the filtrate measured. The amount of copper, cadmium, lead, tin and zinc in the samples were determined. Total dissolved metals in the filtrate were determined by ICPMS and metals on the filters by acid digestion and ICPMS or ICPAES.

---

[2] Government of Western Australia, Department of Fisheries. In-water Cleaning Trial: Report of Sampling Activities. 15 January 2013.

Statistical analysis was performed using the statistical package SPSS Statistics Version 17.0 (*SPSS Inc.*). Analysis of variance (ANOVA) was undertaken first, but including the test for homogeneity of variances. If the significance of the latter test was less than 0.05, non-parametric Mann-Whitney and Kruskal-Wallis tests were applied.

6.4 Observations & Results

6.4.1 Biofouling Removal & Capture

Before cleaning, the surface of the antifouling system on the underwater hull of the *Wambiri* was covered by primary biofouling (= biofilm/microfouling/slime) (Figures 6.2, 6.3). Microscopic examination of a sample taken from the debris on the first stage filtration screen showed the biofouling (>50 µm component) to be primarily diatoms, small filamentous algae and protozoa.

Cart cleaning with both the bladed disc and brushes completely removed the biofilm, and caused no visible damage to the underlying coating (Figures 6.4, 6.5). No plume of either paint or organic debris was visible around the cart during the clean. Removal of the biofilm and leached surface layer of the paint would not cause accelerated deterioration or aging of the antifouling system but, rather, regenerates the antifouling mechanism by restoring the biocide leach rate to, or close to the design rate for the system

Filtrate from the treatment process was visibly (red) coloured during cleaning with both blades and brushes (Figure 6.6), with the colour much more intense during brush cleaning.

Cleaning of the CP anode using the magic box and high pressure water jetting was effective in removing all visible biofouling from on and around the anode (Figure 6.7). No debris or plume was observed to escape the enclosure during the clean, and debris accumulating in the box was seen to be extracted through the suction hose to the trash pump.

Some initial difficulties were experienced in securing the box to the hull around the anode prior to the application of suction which holds and seals the box in position. The box is designed with a central, internal, bendable hook designed to be hooked behind an anode, grate bar or other niche appendage. However the anode chosen did not have sufficient clearance from the hull for insertion of the hook. A magnetic block was therefore placed beside the anode but, with this, there were still some difficulties in attaching the box due to the "hook" straightening and releasing.

Removal of biofouling growth from the wharf pile with the shrouded blade was effective and growth scraped from the surface was drawn into the suction pipe. The observed limitation of the technique related to the severity and thickness of the fouling on the surface. The depth of the fouling exceeded the height of the shroud, and the diver was required to hold clumps of fouling as they were scraped from the surface, and direct them into the suction shroud to ensure they did not fall away from the scraper.

6.4.2 Chemical Contamination Assessment

Water samples collected near the vessel before, during and after *Envirocart* cleaning of the hull indicated no increase in dissolved (Table 6.4.2.1) or particulate (Table 6.4.2.2) copper concentrations in nearby waters as a consequence of the cleaning trial. Some high values were recorded in individual samples which is most likely due to the entrainment of a paint flake or other copper-contaminated particle in individual sample bottles. This occurred in several pre-clean and post-clean samples, with the highest concentration in a pre-clean sample (A-05-2-MIDSHIP-5) with a dissolved copper concentration of 29 µg/L and particulate of 122 µg/L. Of the 90 samples, only 5 had particulate copper concentrations exceeding 10 µg/L and almost all the remainder less than 2 µg/L.

Table 6.4.2.1 Dissolved copper concentrations (Mean ± Std Dev) in filtered water samples collected during the trial

Copper (Dissolved)				
µg/L		A	B	C
		Pre-clean	Mid-clean	Post-clean
0.5 m / stern	0.5m	2.10 ± 0.23	1.22 ± 1.15	1.56 ± 0.43
	2m	2.48 ± 0.60	2.46 ± 1.03	3.74 ± 2.69
2 m / midship	0.5m	8.32 ± 11.75	0.78 ± 0.67	1.80 ± 0.32
	2m	2.68 ± 0.28	0.78 ± 0.68	2.42 ± 0.97
5 m / bow	0.5m	6.49 ± 8.00	1.68 ± 0.74	1.61 ± 1.04
	2m	2.22 ± 0.70	1.84 ± 1.01	0.86 ± 0.77

Table 6.4.2.2 Particulate copper concentrations (Mean ± Std Dev) in water samples collected during the trial

Copper (Particulate)				
µg/L		A	B	C
		Pre-clean	Mid-clean	Post-clean
0.5 m / stern	0.5m	0.56 ± 0.38	1.00 ± 0.58	0.64 ± 0.33
	2m	1.36 ± 0.74	1.60 ± 0.84	7.04 ± 13.96
2 m / midship	0.5m	27.04 ± 53.26	0.48 ± 0.11	0.44 ± 0.17
	2m	2.36 ± 1.34	0.56 ± 0.38	1.68 ± 1.95
5 m / bow	0.5m	15.28 ± 24.74	0.60 ± 0.58	3.72 ± 7.20
	2m	2.52 ± 2.49	1.80 ± 2.30	0.32 ± 0.18

For all data tested, variances were unequal, so non-parametric statistical methods were applied. For both dissolved and particulate copper there was no significant difference between copper concentrations between sampling depths (0.5 m, 2.0 m) or position along the hull (stern, midship, bow). However, the difference in copper concentrations with time (pre-clean, mid-clean, post-clean) was significant (Kruskal-Wallis Test: dissolved, χ^2=18.41, p<0.001; particulate, χ^2=12.89, p=0.02). Post hoc pair-wise testing (Mann-Whitney test) showed the pre-clean dissolved concentrations to be significantly higher than both mid- and post-clean measurements (both p<0.01) and post-clean to be significantly higher than mid-clean (p=0.044). Pre-clean particulate concentration were also significantly higher than mid- and post-clean measurements (both p<0.01) but mid- and post-clean measurements were not significantly different (p=0.68).

As expected, copper concentrations were much higher in the cleaner effluent due to the removal and capture of degraded surface layers of the paint by the cleaning action (Tables 6.4.2.3, 6.4.2.4). Notably, copper concentrations in effluent from the cleaner fitted with the blade head were much lower than those generated by the brush head. Levels of cadmium, lead and tin were all below, or very close to, the limit of detection for the analytical methods used for these metals.

For both dissolved and particulate copper concentrations there was no significant difference between measurements from samples collected in plastic and glass bottles. However, there were significant differences between cleaning mode (idle, blade, brush) ((Kruskal-Wallis Test: dissolved, χ^2=20.53, p<0.001; particulate, χ^2=19.54, p<0.001). Post hoc pair-wise testing

(Mann-Whitney test) showed the dissolved concentrations generated by the machine when idle were significantly lower than both active blades (p=0.001) and brushes (p<0.001), and blades generated significantly less copper than brushes (p=0.001). Particulate copper results were similar, with the idle machine generating significantly less copper than blades (p=0.13) and brushes (p<0.001), and the blades less than the brushes (p=0.001).

Table 6.4.2.3 Dissolved copper concentrations (Mean ± Std Dev) in water samples taken from the cleaner effluent.

Copper (Dissolved)			
µg/L		Plastic sample bottles	Glass sample bottles
Idle	Post UV	81.40 ± 3.71	92.80 ± 37.61
Blade	Post UV	222.00 ± 55.86	
	Pre-screen	82.00	
Brush	Post UV	848.00 ± 94.45	1812 ± 1864
	Pre-screen	850.00	

Table 6.4.2.4 Particulate copper concentrations (Mean ± Std Dev) in water samples taken from the cleaner effluent.

Copper (Particulate)			
µg/L		Plastic sample bottles	Glass sample bottles
Idle	Post UV	6.24 ± 3.90	0.40
Blade	Post UV	19.88 ± 11.35	
	Pre-screen	4.20	
Brush	Post UV	744 ± 271	65.60 ± 20.66
	Pre-screen	1300.00	

6.5 Discussion

6.5.1 Biofouling Removal & Capture

Trials to remove and capture biofouling from the hull of the *MT Wambiri* using the *Envirocart*, magic box and hand scraper all demonstrate complete and effective removal and containment of biological debris. The first stage filtration system was effective in removing all material >50 µm in size, and second stage filtration looked to have removed finer organics evidenced by the absence of scum on foam in the discharge tank. Microscopic examination of filtered effluent would be needed to confirm this.

Difficulties observed in both the initial securing of the magic box to the hull, and the capture of heavy fouling when using the shrouded hand scraper could be easily rectified by minor design modifications. For the box, the use of a rigid hook designed to marry with a magnetic hull attachment (even if an interchangeable unit) should ease the attachment process and, for the scraper, a larger shroud may be necessary for use in the removal of heavy biofouling growth.

6.5.2 Chemical Contamination Assessment

The acceptability of copper concentrations in the marine environment can be guided by acute criteria provided by USEPA and ANZECC provides chronic guidelines from ANZECC based on various levels of protection (80% to 99% of species).

Biocides removed and captured during in-water cleaning include both particulate and dissolved contaminants from the antifouling coatings. The USEPA and ANZECC guidelines above are considered most applicable to the dissolved component of the total biocide concentration. Furthermore, copper speciation and bioavailability is known to greatly affect its toxicity for aquatic organisms. For freshwater, the biotic ligand model has been developed to incorporate the influence of copper speciation and of bioavailability in the presence of competing ions. This model provides site-specific guidelines for different freshwater bodies. A marine-based biotic ligand model has recently been developed for the USEPA, and the critical value for copper in seawater has been determined to be 8.5 µg/L.

As a positive reflection on the magnitude of copper contamination in Fremantle Harbour, dissolved copper concentrations measured around the vessel before, during and after the cleaning trial were almost all below the ANZECC guideline for 90% protection (Table 6.5.2) and the newly established USEPA critical value. However, the important result for the *Envirocart* trial was that there was no indication of elevated copper concentrations in the water column near the test vessel during or after the cleaning trial.

Table 6.5.2 Marine water quality guidelines for copper.

Biocide	*Guideline type*	*Guideline value (µg/L)*	*Reference*
Copper	*Acute (1 hour average)*	*4.8*	*USEPA (1995)*
	Chronic (4 day average)	*3.1*	*USEPA (1995)*
	ANZECC 99% protection	*0.3*	*ANZECC (2000)*
	ANZECC 95% protection	*1.3*	*ANZECC (2000)*
	ANZECC 90% protection	*3*	*ANZECC (2000)*
	ANZECC 80% protection	*8*	*ANZECC (2000)*

Measurements of copper concentrations in the treated effluent from the cleaner are more difficult to interpret in relation to environmental contamination. The clear result was that the blade assembly removed significantly less copper from the hull surface than the brush assembly. The environmental acceptability of direct release of effluent into the adjacent harbour or other water body requires an assessment of the total volume of effluent generated against the volume of the recipient water body, or the level of dilution of effluent prior to discharge. For example, for effluent with a copper content of 250 µg/L, a 30-fold dilution generated by either discharging the effluent into a water body of at least 30 times the volume of the discharge, or diluting each litre of discharge with 30 litres of natural seawater would reduce the concentration to an environmentally acceptable level. Guidance could be obtained from regulations and permits for industrial effluent discharge.

The volume of effluent generated during an *Envirocart* clean of a 45 m vessel hull has been estimated to be approximately 350,000 L (Roger Dyhrberg, pers. comm.). Applying a dissolved copper content of 250 µg/L to this effluent, the total quantity of copper removed would be 87.5 g. Diluting this to the ANZECC 80% protection value of 8 µg/L would require the copper to be diluted within 10,000 m^3 of seawater. The approximate volume of Fremantle Port is 1.8 km x 400 m x 18 m deep, which is close to 13 million m^3.

Another comparison is to the steady state release rate of copper from an effective antifouling coating on a vessel alongside in a port; estimated to be approximately 10 $\mu g/cm^2/day$ (Morrisey et al. 2012). A vessel less than 50 m in length has a wetted hull surface area that can be approximated to 400 m^2, and a vessel 200 m in length has a hull surface area of approximately 10,000 m^2. The estimated daily release of copper from the small vessel is 40 g, and from the large vessel, 1000 g. In the Morrisey et al. study, the copper released by in-water cleaning of a vessel 50-100 m long to remove soft fouling was estimated to be equivalent to that passively released in a day by two vessels 150-200 m in length.

When the trial on the *Wambiri* was conducted, the vehicle carrier *Hoegh St Petersburg* was moored at the adjacent wharf. With a length between perpendiculars of 218 m, this vessel would be releasing approximately 1000 g Cu/day, more than a magnitude greater than the copper estimated to be generated by the *Wambiri* hull clean.

Figure 6.1 Trial 4 test vessel: *MT Wambiri*

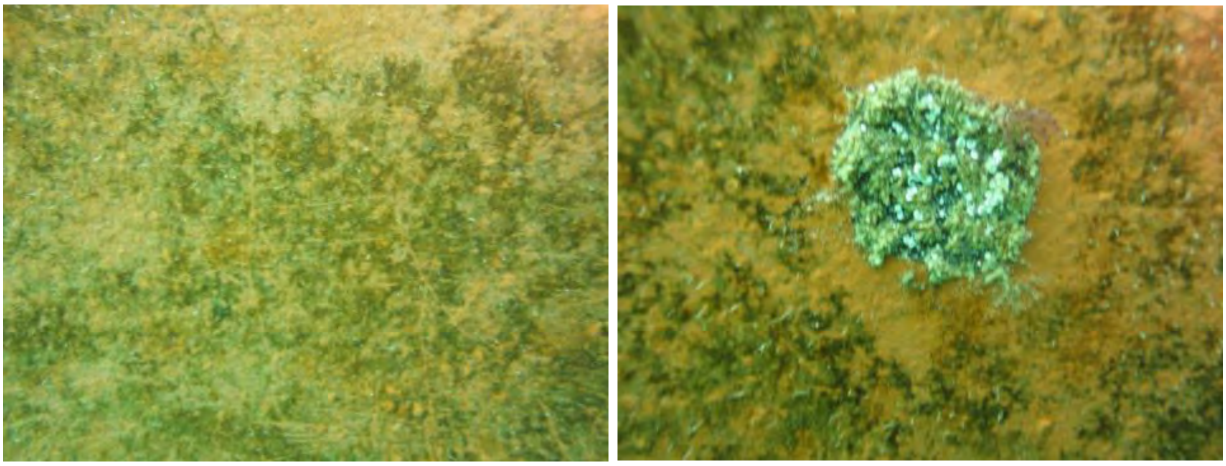


Figure 6.2 Hull surface prior to cleaning.

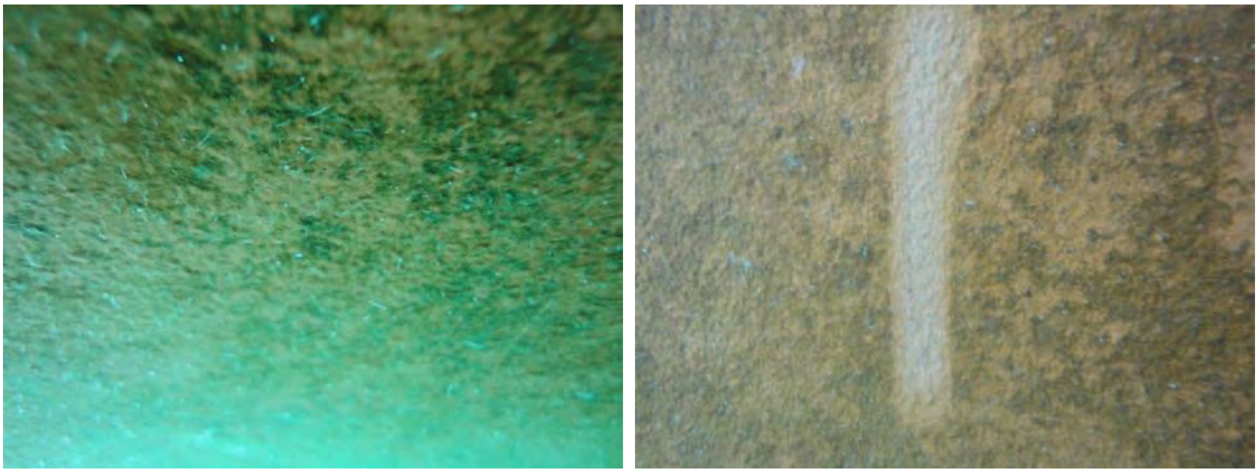


Figure 6.3 Hull surface prior to cleaning.

Figure 6.4 Hull surface after cleaning with the *Envirocart* fitted with bladed discs.

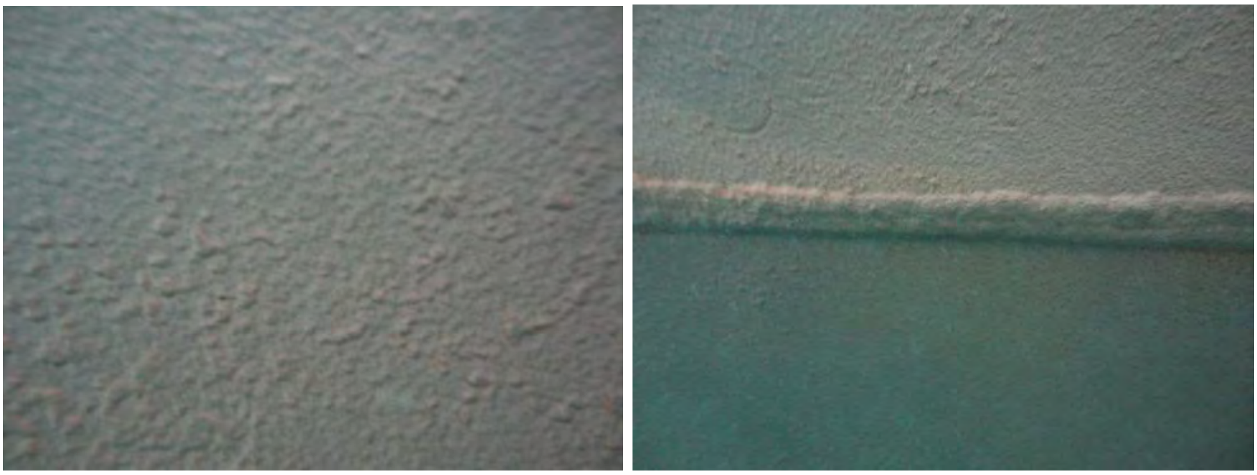


Figure 6.5 Hull surface after cleaning with the *Envirocart* fitted with brushes.

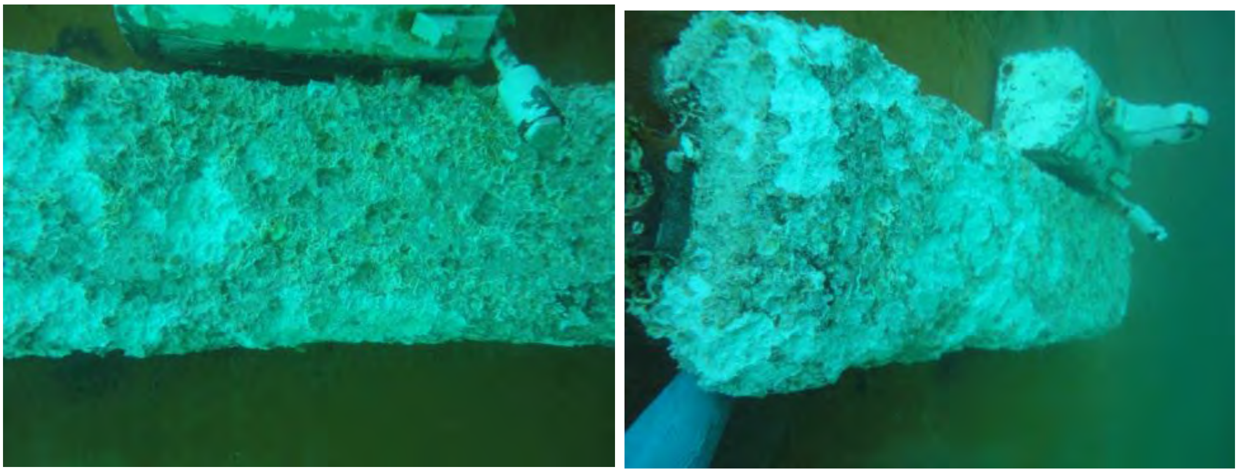


Figure 6.6 CP anode after high pressure water cleaning inside the “magic box”.

Figure 6.7 Red (copper) tinted water flowing over the first stage filter (left), filtrate in the tank below the filter tray (right), during the *Wambiri* hull clean.

Figure 6.8 First stage filtration debris from the box clean of the *Wambiri* anode (left), and scraper clean of the jetty pile (right).

7 GENERAL CONCLUSIONS & DISCUSSION

In the trials conducted in Perth on 26-28 November 2012, the Franmarine "*Envirocart*" in-water hull cleaning and treatment system was demonstrated to be effective in removing, capturing, and containing biofouling growth from representative hull surfaces. Surfaces were cleaned of all visible biofouling and all debris >50 µm was effectively captured by the containment and filtration system.

Deficiencies observes in the system were mechanical and would seem easily addressed by minor design or operational modifications. These include:

- Modification of the jockey wheel on the *Envirocart* to prevent it jamming, dragging and scratching FR coatings;
- Ensuring blade discs cannot loosen and contact the paint surface when cleaning FR coatings;
- Modifying the hook attachment in the magic box; and
- Designing and constructing a larger shroud for hand scrapers for use in manual removal of heavy biofouling.

The assessment of potential chemical contamination from cleaning of biocidal antifouling coatings in Trial 3 found no elevation in environmental levels of copper near the vessel hull during or after the trial clean. The blade assembly removed significantly less copper from the hull than the brush head which is likely due to the non-contact cleaning by the blades. Copper concentrations measured in the effluent may be acceptable for direct discharge into the adjacent water body, but this would require an assessment of the relative volume of effluent generated and the volume of the recipient water body. However, it is estimated that the total quantity of copper generated by the cleaning and entrained in the captured effluent would be significantly less that that released passively in a day from the antifouling paint on the hull of a single commercial vessel berthed in the port. Guidance for permissible discharge into inshore waters could be obtained from regulations on permitted industrial discharge or disposal (e.g. to sewer). Permitted practices in dockyards and other vessel maintenance facilities are likely to be particularly pertinent as the cleaner effluent would be similar to that generated by vessel hull washing after docking. Direct discharge into offshore waters is unlikely to be of concern due to the volume of the recipient water body.

Addressing relevant elements of the DoF requirement for the trial and system (Section 3):

[The system]

- is capable of safely and securely encapsulating and treating (killing and removing bio-foul organisms in a timely manner) a range of vessels types and sizes:
    - Demonstrated;
- Is suitable for 40m vessels in the trial and that can be scaled to accommodate larger vessels (55 m long):
    - Demonstrated;
- Is deployed in the Dampier region to service including but not be limited to, oil and gas industry vessels:
    - Is possible;
- Tests a range of chemical and/or alternate (e.g. anoxia, freshwater) treatments to neutralise marine bio-fouling:
    - Not completely relevant, but the system does UV treat effluent after filtration. Viability studies on effluent would be necessary to prove this, but filtration to 10 µm in the second stage filtration would remove potential propagules;
- Includes a cost-benefit analysis that evaluates the efficacy and suitability (environmental impact, cost, accessibility) of each treatment tested:
    - Reported separately;
- Contains all treatment chemicals and bio-fouling organisms removed from vessel with zero to minimal discharge and/or impact to the surrounding marine environment:
    - Biological containment demonstrated; no treatment chemicals used in this system; treated effluent contaminated by antifouling biocides can be contained for disposal if assessed as unacceptable for direct discharge;
- Safely captures and removes all bio-fouling organisms and residue for analysis and safe disposal:
    - Demonstrated;
- Uses novel techniques such as digital video and/or sonar imaging to provide a record of the extent of biofouling on each vessel:
    - Conventional imaging techniques applied and adequate
- Includes methods that are capable of killing and removing bio-foulers from all areas on a vessel including the hull and vessel bottom, plus niche areas such as propellers, propeller shafts and sea chest grates:
    - Demonstrated in part- hull surfaces were cleaned and the methods for cleaning niches demonstrated, but only a limited number of specific niches were cleaned in this and the previous *Wambiri* trial.

- Allows the DoF, or their representative, to conduct in-situ research to evaluate the efficacy of the system and treatment methods used to kill and capture marine bio-fouling organisms (approximately within one month of development):
  - Facilitated; and
- Includes practical considerations of using these technologies such as start-up and running costs, accessibility and Occupational Health and Safety issues:
  - Addressed.

8 REFERENCES

ANZECC, 2000. Australian and New Zealand guidelines for fresh and marine water quality. National Water Quality Management Strategy Paper No. 4, Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra, Australia.

Floerl, O., Peacock, L., Seaward, K., Inglis, G., 2010. *Review of biosecurity and contaminant risks associated with in-water cleaning.* Department of Agriculture, Fisheries and Forestry, Australia.

Lloyd’s Register Group, 2012. *Ballast water treatment technologies and current system availability. September 2012.* Lloyd’s Register Group Limited, London, UK.

Morrisey, D., Gadd, J., Page, M., Floerl, O., Woods, C., Lewis, J., Georgiades, E., 2012. In-water cleaning of vessels. MPI Technical Paper (unpublished draft). Ministry of Primary Industries, Wellington, New Zealand.

USEPA, 1995. Ambient water quality criteria-saltwater copper addendum (Draft), April 14. Office of Water, Office of Science and Technology, United States Environmental Protection Agency, Washington, DC