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Underwater Ship Husbandry Discharges

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The EPA technical contacts for this document are Ryan Albert (202) 564-0763 and Robin Danesi (202) 564-1846.

SECTION 1

INTRODUCTION

The 2008 Vessel General Permit (VGP) regulates discharges incidental to the normal operation of vessels operating as a means of transportation. The VGP, like other general permits, is issued by the permitting authority (in this case, EPA) and covers multiple facilities within a specific category for a specific period of time (not to exceed 5 years). The 2008 VGP includes the following limits or requirements: general effluent limits applicable to all discharges; effluent limits applicable to 26 specific discharge streams; narrative water-quality based effluent limits; inspection, monitoring, recordkeeping, and reporting requirements; and additional requirements applicable to certain vessel types (USEPA, 2008a).

Because EPA plans to reissue the VGP, the Agency continues to gather information on vessel wastewater sources while examining technologies that can be used to remove pollutants before discharge into waters of the United States.¹ This document contains updated information on recent developments in best management practices (BMPs) for reducing pollutant discharges during underwater ship husbandry.

1.1 WHAT IS UNDERWATER SHIP HUSBANDRY?

Underwater ship husbandry is the maintenance of the underwater portions of a vessel. Underwater ship husbandry, commonly referred to as hull husbandry, is usually initiated in response to marine biofouling of the underwater hull and hull appendages of boats and ships including propellers, rudders, through-hull fittings, and corrosion control equipment. While certain hull husbandry activities such as inspection, cleaning and application of antifouling coatings (AFCs) take place out of the water (in dry dock, slipway or haul-out facilities) others such as hull cleaning and propeller polishing are carried out while the vessel is afloat.

Hull husbandry is practiced by the shipping industry primarily for economic reasons. Biofouling on a ship's hull increases the hydrodynamic drag of the vessel, leading to increased fuel consumption (Chambers et al., 2006). For example, annual cleaning has been estimated to reduce fuel consumption for a 175 m long container ship by 9,000 tons over a 5-year drydocking period (Schat Harding, 2009). Depending on the type of vessel, fuel may make up about 50 percent of the operational costs of a ship, and it has been estimated that fouling increases the annual fuel consumption of the world's commercial shipping fleet by 40 percent, or 120 million tons of fuel at a cost of about \$ 7.5 billion per year (2000 dollars) (GISP, 2008).

Hull husbandry controls biofouling and microbial induced corrosion of the ships' propulsion and seawater cooling systems which can lead to poor maneuverability and engine damage (Chambers et al., 2006).

¹ "Waters of the United States" as defined in 40 CFR 122.2.

1.2 ENVIRONMENTAL IMPACTS OF HULL HUSBANDRY

Hull husbandry practices can have environmental consequences. Two important issues for aquatic ecosystem health that are directly related to hull husbandry include (1) the discharge of toxic chemicals used as biocides in AFCs and (2) biofouling as a vector for aquatic nuisance species (ANS) transport. Underwater hull cleaning using currently available methods can release both toxic chemicals and ANS into receiving waters.

Virtually all vessels that are kept in saltwater use AFCs (Minchin and Gollasch, 2003) to control biofouling of the hull and other underwater equipment. The AFCs that contain biocides prevent the attachment of aquatic organisms to the hull by continuously leaching substances into the surrounding water that are toxic to aquatic life. While a variety of different ingredients may be used in these coatings, the most commonly used biocide is copper. Copper can inhibit photosynthesis in plants and interfere with enzyme function in both plants and animals in concentrations as low as 4 µg/l (Takata et al., 2006). The release of biocides such as copper from hull coatings could lead to water quality impairments, particularly in crowded boat basins. For this reason, copper containing-AFCs are under regulatory scrutiny in a number of locations in the U.S., especially the southern California coastal areas.

Vessel biofouling has been identified as an important pathway for the transport and introduction of ANS (Johnson et al., 2007). While ballast water receives the most attention regarding the movement of ANS, hull fouling is also a significant vector. For example, 90 percent of the 343 marine aquatic invasive species in Hawaii are thought to have arrived through hull fouling (Carlton, 2001), while 36 percent of the nonnative coastal marine species established in continental North America could be attributed to hull fouling (Bax et al., 2003). In comparison, ballast water, by itself, may account for 20 percent of documented invasions (Carlton, 2001). Over the last decade, the possible transfer of species by hull fouling has received growing attention and is now recognized as one of the most important pathways of ANS translocation (Candries, 2009).

1.3 SURVEY OF REGULATIONS AND GUIDELINES FOR HULL HUSBANDRY

Internationally, the 2001 International Convention on the Control of Harmful Anti-fouling Systems on Ships, which entered into force in September of 2008, prohibits the use of harmful organotins such as tributyltin (TBT) in AFCs used on international vessels and establishes a mechanism to prevent the potential future use of other harmful substances in anti-fouling systems. The International Marine Organization's (IMO) Marine Environmental Protection Committee (MEPC) adopted *Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species* at MEPC 62 in July 2011 (IMO, 2011). The management measures outlined within these voluntary guidelines are intended to complement current maintenance practices carried out within the industry. Specifically, the Guidelines address:

- **Choosing the anti-fouling system:** Different anti-fouling systems are designed for different ship operating profiles.

- **Installing, re-installing, or repairing the anti-fouling system:** Whether installing, re-installing or repairing the anti-fouling system, care should be taken in surface preparation to ensure all biofouling residues, flaking paint, or other surface contamination is completely removed, particularly in niche areas, to facilitate good adhesion and durability of the anti-fouling system.
- **Procedures for ship maintenance and recycling facilities:** Ship maintenance and recycling facilities should adopt measures (consistent with applicable national and local laws and regulations) to ensure that viable biofouling organisms or chemical and physical pollutants are not released into the local aquatic environment.

Despite the use of effective anti-fouling systems and operational practices, the MEPC Biofouling Guidelines acknowledge that undesirable amounts of biofouling may still accumulate during the intended lifetime of the anti-fouling system. To maintain a ship as free of biofouling as practical, it may be advisable for the ship to undertake in-water inspection, cleaning and maintenance.

In the U.S., the Vessel General Permit (USEPA, 2008) limits discharges originating from AFCs, underwater ship husbandry, and seawater piping fouling. AFCs and chemicals used for fouling prevention subject to registration under FIFRA (see 40 CFR § 152.15) must be registered, sold or distributed, applied, maintained, and removed in a manner consistent with applicable requirements on the coatings' FIFRA label. For biocides not subject to FIFRA registration (i.e., not produced for sale and distribution in the United States), hull coatings must not contain any biocides or toxic materials banned for use in the United States (including those on EPA's List of Banned or Severely Restricted Pesticides). This requirement applies to all vessels, including those registered and painted outside the United States. The use of TBT AFCs is explicitly prohibited under the VGP, and vessels must remove such coatings or paint over them to prevent toxic leaching². Under the VGP, underwater ship husbandry must be conducted in a manner that minimizes the discharge of fouling organisms and AFCs, and the cleaning of copper-based AFCs must not produce a visible plume of paint.

The U.S. Coast Guard currently addresses hull fouling and hull husbandry related to nonindigenous species through regulations included in 33 CFR §151.2035 that require rinsing of anchors and anchor chains to remove organisms and sediment, and removal of fouling organisms from the hull, piping and tanks on a regular basis. Additionally, although crude oil tankers engaged in coastwise trade are exempt from the requirements of 33 CFR §151.2035 by statute, many tank ship companies conduct voluntary hull maintenance operations, generally in conjunction with regular dry dock inspections mandated by Merchant Class Societies such as the International Association of Classification Societies, Ltd (IACS), and the U.S. Coast Guard.

² The VGP's zero discharge standard for TBT is consistent with the 1998 Organotin Anti-Foulant Paint Control Act, 33 U.S.C. 2403(a) which generally prohibits application of AFCs containing TBT. The zero discharge standard is also consistent with the Convention on the Control of Harmful Anti-Fouling Systems on Ships. The treaty, adopted by the IMO in October 2001, prohibits the use of organotins in antifouling paints. The treaty entered into force on September 17, 2008.

These two entities typically require at least one dry dock inspection of a ship's hull every five years (Takata et al., 2006; USCG, 2000).

Three states have also added requirements related to hull cleaning and maintenance as part of their Clean Water Act (CWA) 401 certifications to the VGP. With the exception of propeller polishing, California prohibits underwater cleaning on all vessels except those using biocide-free AFCs. Biocide-free AFCs have been designated as a "best available technology", and vessels utilizing such coatings may conduct underwater cleaning in California waters (USEPA, 2008). Maine and Massachusetts both prohibit underwater cleaning and fouling removal.

Table 1 provides a summary of the international, United States, and individual State regulations regarding hull husbandry.

Table 1. Summary of Current International and U.S. Management Strategies for Underwater Ship Husbandry

Country or State	Management Strategy	Details
IMO	Guidelines	Develop a biofouling management plan Maintain a biofouling recordbook that details all inspections and biofouling management activities Install and maintain an antifouling systems Conduct in-water inspections, cleaning and maintenance; Design and construct vessels to minimize biofouling.
Australia	Prohibition (States/territories/ports)	States and territories prohibit underwater cleaning. Many require containment and disposal of fouling debris removed during out-of-water cleaning.
	Regulation (Vessels less than 25 m)	Keep ancillary gear and internal seawater systems clean of marine pests and growths, and Before departing your last port for Australia: <ul style="list-style-type: none"> · Clean hull within one month before arrival OR · Apply antifouling paint within one year before arrival OR · Book vessel for slipping and cleaning within one week of arrival (cleaning should be in a shipway where material removed can be collected and disposed of away from the sea)
New Zealand	Import Health Standard (pending)	Vessels arriving from foreign countries would be required to have a 'clean' hull, meaning no visible aquatic organisms, other than a slime layer.

Table 1. Summary of Current International and U.S. Management Strategies for Underwater Ship Husbandry

Country or State	Management Strategy	Details
	Survey (On Ballast Water Declaration Form)	1. When and where was the vessel last dry-docked and cleaned? 2. Has the vessel been laid-up for 3 months or more since it was last dry-docked and cleaned? 3. Do you intend to clean the hull of the vessel in New Zealand?
	Voluntary Code of Practice (Fishing Industry)	Chartered foreign owned or sourced fishing vessels must be substantially free from plant or animal growth prior to entering New Zealand's EEZ. If no assurance, vessel must be inspected and cleaned before departure. If otherwise inspected in NZ and if necessary, fouling must be removed so no foreign organisms enter the marine environment.
Australia and New Zealand Environmental Conservation Council (ANZECC)	Codes of Practice	Underwater hull cleaning prohibited, except under extraordinary circumstances. Sea-chests, sea suction grids, other hull apertures may be allowed under permit, if debris not allowed to pass to water column or sea bed. Polishing propellers may be allowed under permit.
United States	VGP	Underwater ship husbandry must be conducted in a manner that minimizes the discharge of fouling organisms and antifouling hull coatings, and the cleaning of copper-based AFCs must not produce a visible plume of paint. Rinse anchor chains and anchors at place of origin. Remove fouling from hull, piping and tanks on a regular basis. Dispose wastes in accordance with local, state, and federal law.
California	State VGP 401 certification requirement	Propeller cleaning is allowed until January 1, 2012. All other underwater hull cleaning is prohibited without special permission from the State Lands Commission (SLC) and State Water Board. Submit annual Hull Husbandry Reporting Form. Rinse anchor chains and anchors at place of origin Remove fouling from hull, piping and tanks on a regular basis. Dispose wastes in accordance with local, state, and federal law.

Table 1. Summary of Current International and U.S. Management Strategies for Underwater Ship Husbandry

Country or State	Management Strategy	Details
Hawaii	Information Framework Targeting High Risk Vessels (Proposed)	Pro-active measures: Education/outreach, vessel arrival monitoring, evaluation for high-risk arrivals Re-active measures: Rapid response/investigation of high risk event Post-event measures: Long term regulations for high-risk events Limit time in port Vessel quarantine Out of water cleaning
Maine	State VGP 401 certification requirement	No vessel may conduct underwater hull cleaning except as part of emergency repairs
Massachusetts	State VGP 401 certification requirement	Hull husbandry discharges are prohibited within 3 miles of shore.
Merchant Classification Societies	Requirements (Applies to majority of merchant fleet)	Dry dock requirements vary somewhat depending on classification society. Cleaning and painting is usually conducted, but is at the discretion of the company. Interim underwater cleanings are done periodically at the discretion of the company, typically dependent on results of fuel consumption tests.

Source: Takata, 2006.

IMO: International Maritime Organization

SECTION 2

FACTORS EFFECTING BIOFOULING

Biofouling organisms attach to submerged hard surfaces of both naturally occurring and man-made structures (Railkin, 2004). Species that foul vessel hulls are typical of natural, marine intertidal and subtidal fouling communities. Marine fouling communities can include arthropods (barnacles, amphipods, and crabs), mollusks (mussels, clams, and sea slugs), sponges, bryozoans, coelenterates (hydroids and anemones), protozoans, annelids (marine worms), and chordates (sea squirts and fish), as well as macroalgae (seaweed). If these fouling communities become highly developed they can also provide micro-habitats for mobile organisms such as fish.

Typically, there is a progression of attachment of marine organisms to a vessel's hull (Floerl et al., 2010). Primary biofouling begins as soon as the surface of a vessel is submerged in seawater, with the formation of a slime layer consisting of bacteria and microscopic algae. As the vessel remains submerged in seawater, secondary biofouling occurs as organisms settle on top of the primary biofouling layer. Secondary biofouling usually includes hard encrusting animals such as acorn barnacles, bryozoans and serpulid worms, but may also include soft algal tufts and mobile amphipods. If the hull is coated with an AFC containing a biocide, the toxicant will act to deter the attachment of higher forms such as barnacles and tubeworms, but will usually allow primary biofouling within days or weeks of launching with fresh AFC.

Although biofouling progresses in a predictable manner, it is not a uniform process. For example, biofouling is not evenly distributed on submerged portions of vessels because a vessel's hull is not a uniform surface. Certain movement patterns and environmental factors have been observed to affect the diversity (variety of species) and the quantity of biofouling observed on commercial vessels. The factors likely to affect the rate of biofouling include:

- Immobile periods;
- Vessel speed;
- Voyage duration;
- Voyage movement patterns; and
- Environmental factors (salinity, temperature and nutrients).

These factors influence the ability of free swimming or floating organisms to attach to a vessel and remain affixed, or affect the ability of the organism to survive voyages. Each of these factors is discussed in the following sections.

2.1 IMMOBILE PERIODS

The level of fouling is related to the amount of time a vessel spends in port (Cordell et al., 2009). In general, the longer a ship stays pierside, the more likely it is to accumulate fouling. Many floating or free swimming organisms are better able to attach or "settle" on surfaces while vessels are immobile, and vessels that spend long stationary periods have been observed to have heavier fouling communities (Coutts, 1999). Because larval settlement may be prevented by speeds as slow as 2 knots (Davidson et al., 2006), accumulation predominantly occurs while a vessel is docked, and increases over time. This is especially true in protected ports with restricted

flow and poor flushing where propagules (the small, dispersing larval phase of marine invertebrate life cycles) may be retained in the water column for long periods of time (Takata et al., 2006).

Assuming suitable environmental conditions, biofouling is likely to increase with the residence time of a vessel (Floerl et al., 2005), by providing attached organisms sufficient time to become reproductively viable. However, it is worth noting that some vessels may also visit a port or region where suboptimal environmental conditions prevail (e.g. low salinity, high turbidity), and in such cases, ANS release risks may be mitigated through die-off of the fouling organisms.

Typically, most commercial ships operate the majority of the time, while naval vessels may spend long periods of time pierside. For example, commercial ships may be at sea 85 percent or more as they only generate revenue when delivering cargoes (Bohlander, 2009), the exception being commercial vessel inactivity due to economic downturn. In contrast, the general operating cycle for the U.S. Navy vessels is between 40-60 percent pierside with the rest at sea (US Navy and USEPA, 2003). With the decline in fish catches in many parts of the world, many commercial fishing vessels are underutilized and poorly maintained, with vessels being laid up and/or sold off for other purposes. These vessels may represent a considerable risk in terms of hull fouling due to the time they are pierside (Candries, 2009).

2.2 VESSEL SPEED

Vessel speed influences the quantity and diversity of fouling species observed on vessels. At high speeds, many organisms are unable to remain attached to vessel hulls because they cannot endure the forceful water moving past the surface. Less robust organisms may be dislodged or may be unable to survive. In contrast, slow speeds are less stressful, allowing many fouling organisms to remain attached or continue settling on the vessel surface (Takata et al., 2011). Thus, slower moving vessels have been observed to accumulate thicker fouling than faster vessels that travel over 18-20 knots (Michin and Gollasch, 2003).

Vessel speed can also affect the survival of invasive species. Long-distance travel is becoming easier and faster. This enables more invasive species to survive long enough to reach a new environment (Ruiz et al., 2000). For example, *Cordylophora caspia*, a hydroid that lives in both freshwater and brackish water, may have been transported successfully because of an increase in ship speeds (Johnson et al., 2007)

Boats that travel at slower speeds are also susceptible to invasions because more species can attach firmly to their hulls (Michin and Gollasch, 2003). Furthermore, some nontoxic AFCs may only be effective if the vessel travels regularly at 15 knots to 20 knots (Swain et al., 2001). Such coatings would be ineffective in preventing attachment of invasive species on hulls of vessels that seldom or never reach or exceed those speeds (Johnson et al., 2007).

2.3 VOYAGE DURATION

Shorter voyages have been observed to be more advantageous for the survival of coastal fouling organisms and communities than longer voyages. The prolonged exposure to harsh physical conditions of the open ocean during a long voyage may be detrimental to fouling organisms, or they may be deprived of food for an untenable length of time (Coutts, 1999). Ships

with effective AFCs tend to lack fouling if the vessel has traveled for 9.75 days or more in open waters (Johnson et al., 2007).

2.4 VESSEL MOVEMENT PATTERNS

The expansion of global trade has led to significantly more ballast water, fouled hulls, and associated organisms moving around the world (Minchin and Gollasch, 2003). Each year there are approximately 1.7 million visits by vessels to the world's 4,700 ports (Etkin, 2010). In the U.S., there are about 110,000 annual vessel visits to ports and other places (Miller et al., 2007).

Large estuaries with international shipping serve as sources for species that become invasive in other geographic regions. In other words, larger ships likely accomplish most of the long-distance transport (primary introduction) while commercial fishing and recreational boats likely contribute to the transport of invasive species along the coast (secondary introduction) (Johnson et al., 2007).

Traveling to a wide range of locations may also be an ANS risk factor because it increases the likelihood that an organism with a broad range of tolerances will attach to a vessel hull. Furthermore, a number of ANS have been introduced far outside their places of origin, and are becoming pandemic. In these cases, the rate of new introductions is accelerating, possibly due to increasing sources for secondary introductions, and the spread of physiologically tolerant ANS (Cohen and Carlton, 1998).

For example, secondary introduction poses a risk to Alaska from domestic and coastwise ports. Introduced species have already demonstrated an ability to successfully colonize these Alaskan waters. A combination of factors such as fewer temperature and salinity changes and shorter voyages may mean that there is a higher risk of secondary ANS contamination of Alaskan waters from vessels traveling on coastal voyages (e.g., from Puget Sound or San Francisco Bay) than of primary contamination from vessels traveling from more distant locations.

Cordell et al. (2009) analyzed shipping patterns in Prince William Sound, Alaska. They identified two categories of vessels: those that have set routes and make numerous brief return trips to the same port, and those that return to port infrequently but stay in port for long periods of time. The first type presents a risk of repeat inoculations of ANS (potential high propagule frequency), and the second represents ANS risk based on less frequent inoculations with longer "incubation" time for ANS to release propagules (potential high propagule volume). Tank ships and passenger vessels represent the high frequency risk category, while freight and fishing vessels represent the high volume risk category. Commercial fishing and commercial passenger fishing boats share some features of commercial shipping: they travel often and some go to distant fishing grounds. They also share some features of recreational boats: they may spend much time within a region and many are small craft, whose underwater structures are more like those of pleasure craft than commercial cargo ships, tugs and barges (Johnson et al., 2007).

Movements of military vessels also create pathways for ANS introduction. Invasive species have been documented on the hulls of military vessels in Hawaii. Analyses of benthic organisms and fishes of Pearl Harbor sampled in 1996 suggests two periods of relatively high introduction rates corresponding to wartime periods. Most of the introduced species with known

geographic origins have distributions extending to the Indo-West Pacific. However several species are known from the Red Sea and the Caribbean Sea (Coles et al., 1999).

2.5 ENVIRONMENTAL FACTORS (SALINITY, TEMPERATURE AND NUTRIENTS)

The accretion of marine fouling can be highly variable, depending on geographical location, time of year, and seasonal variations in weather. In general, fouling flourishes during warmer months and diminishes in cooler months. Due to reproductive periodicity of fouling organisms, propagule amounts can vary by season, with summer and spring typically having higher propagule numbers than winter and fall (Davidson et al., 2006). Fouling organisms may also release viable propagules in response to new environmental cues (e.g., altered salinity or temperature) in a recipient region and inoculate surrounding habitats including artificial structures (Minchin and Gollasch, 2003).

Vessels that operate in waters with rapid and drastic changes in salinity and temperature, such as those that pass through both marine and fresh water or conduct transequatorial voyages, may experience reduced survivorship of fouling organisms by subjecting them to a range of conditions outside their physiological limits (Davidson et al., 2006; Takata et al., 2006). On the other hand, Coutts and Taylor (2004) found that vessels that travel through similar latitudes may experience increased survivorship of fouling organisms by retaining relatively consistent temperature and salinity levels.

Ocean warming due to climate change will stimulate the growth of barnacles and other biofouling organisms, potentially adding billions in operational costs of worldwide shipping (Williams, 2011). In laboratory tests for which seawater was warmed 3.5°C above current averages (a scenario that represents ocean water temperatures expected in the year 2100), organisms in a typical biofouling community grew twice as fast as they do under current conditions, and formed a thicker layer of fouling. In addition, increased fouling from ocean warming may increase risk of ANS transport. Ocean warming also compounds the problem of ANS by opening new routes for invasions, such as the Northwest Passage which has been ice-free since 2007, and by favoring the colonization, survival, and growth of some invasive species over native species.

SECTION 3: ANTIFOULING COATINGS

AFCs are the primary mechanism for reducing biofouling of the underwater portions of vessels. AFCs can be categorized into: a) those that control hull biofouling by releasing biocides and b) non-biocidal coatings, which (most commonly) provide surface characteristics that inhibit the attachment and adhesion of biofouling organisms. Each of these types of AFCs are discussed in the sections below along with best management practices to minimize their release during hull husbandry activities.

3.1 AFCs CONTAINING BIOCIDES

Virtually all vessels that are permanently kept in saltwater use AFCs, and the majority of AFCs presently in use contain biocidal chemicals to inhibit the colonization of the vessel's hull (Minchin et al., 2003). These chemicals, which are toxic to fouling organisms, are slowly released from the coated surface into the surrounding waters. The primary constituent used in most biocidal AFCs is copper, although zinc may also be used as an ingredient.

While the rate at which the metals leach from coatings is relatively slow (4 – 17 $\mu\text{g}/\text{cm}^2/\text{day}$), these coatings can account for significant accumulations of metals in receiving waters of ports where numerous vessels are present (USEPA, 2010). Copper-based coatings have the potential to cause environmental harm. For example, high copper concentrations at California's Shelter Island Yacht Basis (SIYB) of San Diego Bay threaten sediment quality and may potentially adversely impact benthic life. The State Water Resources Control Board will require a 76 percent reduction of copper discharges from antifouling paints in SIYB by 2022 (California Regional Water Quality Control Board, San Diego Region, 2006). Ninety-three percent of the copper in the SIYB was attributed to the passive leaching of copper-based AFP pesticides that have been applied to boat hulls. Copper released from underwater hull cleaning contributed 5 percent (Singhasemanon, 2010). Other parts of San Diego Bay have been listed on the California SWRCB 303(d) list of impaired water bodies for dissolved copper and actions in other southern California boat basins suggest copper-containing AFCs may soon be restricted elsewhere in the region (California Regional Water Quality Control Board, Los Angeles Region, 2005; USEPA, 2002).

Increased biocide release rates may also occur during hull husbandry activities, particularly if hulls are cleaned within the first 90 days following AFC application (Schiff et al., 2003).

The predominant AFCs on the commercial market are briefly discussed below.

Insoluble Matrix / Contact Leaching / Hard Coatings

Conventional insoluble matrix or 'contact leaching' systems are based on hard, porous resins that are insoluble and do not erode in seawater (Floerl et al., 2010). Examples of these compounds include acrylic, vinyl, epoxy and chlorinated rubber polymers (AMOG, 2002). Modern hard-type formulations (which are usually based on modified epoxy matrices) provide improved control over biocide release rates, particularly for copper-based coatings, with effective life expectancies of between 24 and 36 months (Floerl et al., 2010). Of the AFCs commonly used today, hard-type coatings provide the best resistance to damage by abrasion,

affording successful protection for vessels, or areas of vessels, that are subject to elevated levels of wear. An advantage of this coating type is that the hard, insoluble matrix is resilient to damage by oxidation, providing a longer coating life Almeida et al., 2007).

Controlled Depletion Polymer / Ablative Coatings

Controlled depletion polymer (CPD) systems are also known as ablative coatings. Ablative coatings are designed to slough off layers of matrix and biocides as water moves over the hull surface, providing a self-polishing mechanism to maintain hull smoothness. This process also promotes self-cleaning by presenting an unstable, biocidal surface for biofouling organisms. CPD coatings provide effective biofouling protection and, since thicker layers of CDP coatings can be applied in comparison to conventional soluble matrix systems, the effective life is increased to up to 36 months in suitable conditions. However, traditional hull-cleaning techniques, such as scrubbing, can damage and remove the coating and shorten the life span. CDP coatings provide the lowest cost per meter squared of AFC and are suitable for use in low biofouling conditions or by vessels with short drydock intervals (Floerl et al., 2010). They are widely used by recreational vessels and small ships (Almeida et al., 2007).

Self-polishing Copolymer Coatings

The ban on the use of TBT as a biocide has prompted the development of alternative TBT-free self-polishing copolymer coatings (SPCs). This “new technology” of TBT-free SPCs uses copper acrylate, zinc acrylate and silyl polymers in-place of TBT (Floerl et al., 2010). TBT-free SPCs are claimed to provide self-polishing performance, controlled biocide release rates and long-term performance comparable to TBT-SPCs. New products are marketed with effective working lives similar to TBT-SPCs (up to 60 months). Almeida et al. (2007) indicate that the maximum service life of this type of coating is usually three years, but effective life spans of up to five years have been reported.

3.2 NON-BIOCIDAL AFCs

It has long been a goal of paint companies to produce an antifouling paint that does not contain toxic ingredients (Bohlander, 2009). There are several benefits to such a coating, including less stringent environmental regulation for use and disposal, no or low impact on the local marine environment from the leaching of toxic ingredients into the water column, reduced hazards to the shipyard workers applying and removing the paints, and reduced generation of hazardous materials during application and removal. Recent research and development efforts have therefore focused on alternative antifouling mechanisms and non-biocidal active compounds that can provide ‘environmentally safe’ options (AMOG, 2002).

Several biocide-free systems are in development, but currently the systems that have been developed and successfully marketed are based on “non-stick” silicone based fouling-release technology. These coating systems provide surface characteristics that aim to prevent the adhesion of biofouling organisms or allow biofouling to accumulate, but prevent adhesion as organisms grow or are subjected to water movement (Floerl et al., 2010). Fouling-release coatings provide an expected effective life of five years or longer (AMOG, 2002), but are more difficult and expensive to apply than other AFCs.

Antifouling success of fouling-release coatings currently relies on vessel speed and movement to dislodge any organisms that do attach. Self-cleaning of hulls has been demonstrated for vessels that frequently maintain speeds between 15 and 30 knots, depending on the biofouling community (AMOG, 2002; Chambers et al. 2006; Floerl et al., 2010). Coating manufacturers claim propulsive fuel efficiencies of 3-11 percent, which can be realized if the ships using these products cruise at speeds ranging from 10-18 knots, and spend relatively little time pierside (Floerl et al., 2010). Therefore, this technology is currently best suited to fast-moving vessels with rapid port turn-around periods and sufficient activity levels. The fouling-release AFCs are establishing a market in commercial shipping fleets, primarily with cruise ships and fast container ships, as these vessels have operational profiles that are suitable for use of foul release paints.

There are several manufacturers of fouling release paints, with a variety of products on the market. All share the characteristic of generally allowing marine fouling to attach to the coating while the ship is pierside, then claiming the biofouling will detach with ship movement. However, it is also possible that ships using fouling release coatings could transfer ANS from one location to another if the coating does not completely self-clean. There is also likely to be variability in performance for these products, and while they are in regular commercial use, it will take additional time to get a clear indication of the benefits and operating characteristics of these materials as well as their potential for ANS transmission. Fouling-release coatings may still require hull cleaning. There is a possibility that the cleaning process may damage these coatings, allowing increased fouling growth. The underwater cleaning of fouling-release or other non-biocidal AFCs can still pose an environmental risk via the uncontrolled release of ANS during the cleaning operation.

3.3 BEST MANAGEMENT PRACTICES FOR AFC LEACHATE

In the 2008 VGP, in addition to prohibiting the discharge of TBT, EPA identified two main BMPs for control of AFC leachate. The first type of BMP regards applying coatings according to the instructions on the coating's FIFRA label when applicable. The second type of BMP addresses the need for particular coatings and selection of the type of coating to apply. EPA noted that the vessel owner/operator must consider the fouling rate of the hull and other underwater areas of the vessel, the vessel's operating speed, the drydocking frequency, and the waters in which the vessel will be traveling when selecting the appropriate antifouling system for a particular vessel.

A third potential BMP regards matching the coating's abilities or strength to drydock cycles. Larger vessels, particularly those used in trade and cargo transport, must adhere to requirements for safety inspections and maintenance activities that dictate how frequently they must be drydocked. The major manufacturers of hull coatings for this industry guarantee the effectiveness of their products for a certain period of time based on ship and operational characteristics; vessel owner/operators could match the hull coating choice to the appropriate drydocking interval. By factoring this schedule into the hull coating selection, vessel operators could select coatings that would sufficiently protect the vessel for the period of time needed while reducing unnecessary leachate or wastes.

SECTION 4**HULL HUSBANDRY BEST MANAGEMENT PRACTICES**

Regulatory agencies have begun developing BMPs for hull husbandry practices to prevent and/or control the transport and introduction of ANS by commercial shipping and to reduce the loss of AFCs to surface waters during hull husbandry activities. Table 2 summarizes vessel husbandry BMPs for various international organizations, states and classification societies.

In general, BMPs for hull husbandry require that rigorous hull-cleaning activities take place while the vessel is in drydock, or another land-based facility where the removal of fouling organisms or spent antifouling paint can be contained and treated. In the 2008 VGP, EPA required that vessel owner/operators who must perform hull husbandry while the vessel is in the water should use methods that minimize the discharge of fouling organisms and AFCs. These methods include (USEPA, 2008):

- Selection of appropriate soft cleaning brush or sponge rigidity to minimize the release of paints and hull materials including AFCs into the water column;
- Limiting use of hard brushes and surfaces to the removal of hard growth; and
- Use of vacuum cleaning technologies (when available) in conjunction with mechanical scrubbing, to minimize the release or dispersion of AFCs and fouling organisms into the water column.

EPA also requires vessel owner/operators to minimize the release of copper based antifoulant paint into the water column when they clean the vessel. Cleaning of copper based antifoulant paints should not result in any visible cloud or plume of paint in the water, and if one develops, then the person doing the cleaning should change to a softer brush or less abrasive cleaning technique (USEPA, 2008).

Table 2. Hull Husbandry Best Management Practices (BMPs) for International Organizations, the U.S., States and Classification Societies

Hull Husbandry BMP	IMO	US EPA (VGP)	California	Maine	Massachusetts	Merchant Classification Societies
Out-of-Water Hull Maintenance		Whenever possible, rigorous hull-cleaning activities should take place out of water, where fouling organisms and AFCs can be contained. Use facilities which treat wash water from high-pressure washing prior to discharge.	Remove fouling by physical cleaning (e.g., hull and niche cleaning during the vessels scheduled 5 year out-of-water dry-docking).		All hull cleaning shall occur while a vessel is in drydock or at another landside facility so that wash water and hull cleaning residuals can be collected and disposed of properly.	Generally require vessels to be dry docked at least once every five years. None of the societies requires the hull to be cleaned while dry docked, but most companies do.
Underwater Hull Cleaning	Follow applicable regulations/ requirements for underwater cleaning. Use cleaning techniques that minimize release of biocides for hulls coated in biocidal AFCs. Remove macro-fouling growth in accordance with regulations. Minimize release of AFC debris and viable macrofouling organisms by soft cleaning	Use cleaning techniques (e.g., select appropriate brush, contain debris with vacuum system) that minimize discharge of fouling organisms and AFCs. Cleaning copper-based AFC must not produce visible plume of paint.	All underwater hull cleaning is prohibited unless conducted using the best available technologies economically feasible (e.g., allowed for biocide-free AFCs, not allowed for copper-based AFCs in impaired waters).	Prohibited except as part of emergency hull repairs necessary to secure the vessel.	Discharges associated with under-water ship husbandry (specifically the removal of fouling organisms) are prohibited in waters within 3 nm.	Although not required, most companies also conduct interim under-water cleanings according to fuel performance tests, in order to maintain cost effective fuel efficiency.
Underwater Cleaning of Sea Chests and Niche Areas	Outlines management measures for niche areas.					
Propeller Polishing	Recommends regular polishing of uncoated propellers		Propeller cleaning is allowed until January 2012. After that date, propeller cleaning will be allowed only as specified in regulations adopted by SLC.			
Rinse Anchors and Anchor Chains		Rinse to remove organisms/sediments at their place of origin.				

SECTION 5

VESSEL HUSBANDRY DEBRIS CONTAINMENT OPTIONS

Underwater hull cleaning can be quite effective at removing marine fouling; however, the effluent stream from cleaning is difficult to control. Standard underwater hull cleaning tools, including multi-brush and single brush tools, typically have no inherent capability to contain the discharge of coatings and biofouling organisms removed during hull cleaning. Instead, these particulate materials are commonly released into the water column.

The potential for water quality impairment and ANS release resulting from the uncontained discharge of underwater cleaning effluent is widely recognized. For example, underwater hull cleaning has been banned according to the ANZECC Code of Practice (ANZECC, 1997).

Due to this scrutiny, a number of underwater cleaning technologies have been developed to retain the abraded paint, rust, and biofouling organisms. At present, several of these systems are becoming commercially available. Bohlander (2009) conducted a review of underwater hull cleaning practices, and found four systems that were designed to contain and capture cleaning effluent and transfer this wastewater stream to the surface for treatment. These systems include: 1) the U.S. Navy Advanced Hull Cleaning System (AHCS) and Automated Hull Maintenance Vehicle (AHMV), 2) the modified SCAMP from Seaward Marine Services, 3) the HISMAR system based in the United Kingdom, and 4) the Norwegian CleanROV system.

Two of these systems are currently being used for hull cleaning: the AHCS and the CleanROV. Only one of these systems, the AHCS, includes a wastewater treatment system along with the capability to process larger calcareous fouling. The AHCS fulfilled most of the need for contained hull cleaning, although it was developed specifically for the Naval Sea Systems Command (NAVSEA) and is not available to commercial vessels at this time. The AHCS and the CleanROV systems are discussed in the following sections.

5.1 U.S. NAVY ADVANCED HULL CLEANING SYSTEM (AHCS) AND AUTOMATED HULL MAINTENANCE VEHICLE (AHMV)

The U.S. Navy developed a prototype multi-brush hull cleaning system that captures the debris generated from hull cleaning and transports it to the pier for processing in a mobile treatment trailer. The AHCS was developed primarily to reduce the amount of copper discharged during hull cleaning of U.S. Navy ships. It was not specifically developed to process marine biofouling, although biofouling is also contained and processed by the system.

Floerl et al. (2010) also reported on the development of an Automated Hull Maintenance Vehicle (AHMV), a specialized remotely operated vehicle (ROV) technology developed for automated underwater hull maintenance and inspection of U.S. Naval ships. The unit addresses the expense and environmental implications of traditional diver-operated cleaning equipment that discharge potentially toxic effluent into the marine environment, along with biofouling debris and potential ANS (Floerl et al., 2010). Biofouling is cleaned from the hull using rotating brushes incorporated into the unit, and the debris is collected by a vacuum-sealed mantle that

surrounds the AHMV. Particulate matter is transported to the surface for treatment (filtration to remove particles > 20 microns (μm) via filtration) and disposal.

The AHCS and AHMV have the potential of saving the U.S. Navy 10 percent on fuel-costs, and may result in lower environmental impact from the routine cleaning of navy vessels. Floerl et al. (2010) were unable to obtain detailed information on test results of these units, particularly on the AHMV's effectiveness at removing biofouling from targeted areas and at collecting and containing biofouling and paint waste. Since no additional information could be found, it is difficult to assess the availability of these technologies for hull husbandry of commercial vessels.

5.2 SCAT HARDING (NORWAY) CLEANHULL AS

The Norwegian company Scat Harding developed the CleanHull AS, a ROV for underwater hull cleaning with integrated water filtration and waste recovery. The CleanHull AS is designed to clean large, flat surfaces with minimum curvature and biofouling assemblages at early stages of development (e.g., algal growth and small barnacles). Preliminary (and unpublished) test results indicate an effectiveness of close to 100 percent in removing biofouling from such areas (Floerl et al., 2010). CleanHull AS cannot clean niche areas such as propellers, rudders, thrusters or similar irregular structures. Biofouling is removed from hull surfaces using an underwater high-pressure water blast. The power of the water-blast varies depending on the type of AFC on the hull (e.g., silicone-based paints require gentler treatment).

The removed biofouling material is captured via a particulate containment system that includes a vacuum that pumps the recovered material into a filter unit. The company estimates that approximately 98 percent of the biofouling material removed during cleaning is captured and contained during this process. However, supporting documentation was not supplied and no information is available on the particle sizes that can be captured by the system (Floerl et al., 2010). Apparently, extensive testing in collaboration with several major AFC manufacturers has been undertaken. Results (which were also not available to Floerl et al.) indicate that the water-blasting action of CleanROV has no negative effect on the performance of the AFCs, including biocide-free silicon-based products. This is seen as its principal advantage over more abrasive techniques such as rotating brushes.

Scat Harding offers fleet service agreements involving multiple treatments per year. The ROV is not intended for use on heavily fouled ships, as the principal objective of the system is to preserve or reinstate the performance of a ship's AFC. The CleanHull AS services are currently offered at ports in Norway; in the Skagerak Strait; Vlissingen and Rotterdam in the Netherlands; Algeciras, Spain; Southampton, UK; United Arab Emirates; and Singapore (Scat Harding, 2009).

SECTION 6

HULL HUSBANDRY COSTS

Although hull husbandry can facilitate the release of ANS and pollutants such as copper, cleaning biofouling from the hulls and niches of commercial vessels reduces hydrodynamic drag and the associated increase in fuel consumption. Floerl et al. (2010) developed cost estimates for hull and niche cleaning of commercial vessels with lengths ranging from 25 to 200 meters. Costs were estimated for both out-of-water (slipway and drydock) and underwater cleaning by available technologies, based on quotes obtained from facilities and professional cleaning crews in Australia and New Zealand. These cost estimates are presented in Table 3.

The cost estimates in Table 3 have been converted from Australian to U.S. dollars and, as noted by Floerl et al. (2010), are subject to large variations in rates charged by providers of these services. The costs of services such as drydocking, slipway hire, professional cleaning crews for water-blasting and painting, charges for water usage, waste removal and treatment and other associated activities vary greatly between facilities and countries. Furthermore, the cost estimates do not include the lost revenue incurred while vessels are traveling to and from cleaning facilities and the time out of service while waiting to be cleaned.

As indicated by Table 3, the cost for removing a medium-sized ship (25–60 m in length) from the water in a slipway and cleaning via water-blast is approximately \$2,800–\$12,000, excluding lost operating revenue. The application of AFC following cleaning is estimated to cost an additional \$6,500–\$24,500.

The costs for dry docking and cleaning a 25–60 m vessel using high-pressure water-blast (8,000 psi) at a New Zealand drydock ranges from \$8,800–\$28,800 depending on vessel size. The application of additional AFC will add \$34,900–\$87,900 depending on vessel size.

Cost estimates for advanced underwater hull cleaning technologies using rotating brushes and water blast combined with a particulate containment system are also provided in Table 3. The estimated cost of underwater removal of biofouling from all hull and niche areas of a 50 m long ship range from \$10,300 to \$26,300, plus one to two days of lost revenue. For vessels ranging in size from 100 to 200 meters in length, these costs increase to as much as \$96,000 plus three to five days of lost revenue while the vessel is being cleaned.

Table 3. Estimated Costs of One-Time Out-of-Water and Underwater Hull Husbandry

Location	Treatment	Vessel Length (meters)					
		25	40	50	60	100	200
Slipway (out of water) (Australia)	Hull Cleaning via Water Blasting	\$2,800	\$6,300		\$12,000		
	Apply new AFC*	\$6,500	\$15,200		\$24,500		
Drydock (New Zealand)	Hull Cleaning via Water Blasting	\$8,800	\$13,200		\$28,800		
	Apply new AFC*	\$34,900	\$55,600		\$87,900		
Drydock (Australia)	Hull Cleaning via Water Blasting			\$25,900		\$83,800	\$191,400
	Apply new AFC*			\$29,500		\$146,300	\$417,200
Underwater	Hull Cleaning via Diver-Operated Rotating Brush and Particulate Containment System			\$10,300-\$19,100		\$20,300-\$30,800	\$64,100-\$76,400
Underwater	Hull Cleaning via ROV Water Blast and Particulate Containment System			\$12,100-\$26,300		\$25,500-\$41,200	\$79,800-\$96,000

Source: Adapted from Floerl et al., 2010.

Note: * AFC application is a cost in addition to hull cleaning.

The cost of underwater cleaning of hull and niche areas using technologies that remove biofouling organisms from a vessel hull (i.e. brushes and water-blast) is generally lower than the cost for removing a vessel from the water for cleaning only. However, because of variation in the rates different operators charge for the same service, the relative difference in cost between underwater and shore-based water cleaning is also variable. Nevertheless, for commercial vessels of 50–200 m in length, a comprehensive underwater hull cleaning is 35–65% less expensive than biofouling removal at a slipway or drydock. This difference in cost may further increase when indirect costs such as losses in revenue are incorporated. However, several factors offset the cost savings of underwater cleaning relative to out-of-water cleaning. The effectiveness of underwater cleaning operations is likely to be lower than that of cleaning activities out of the water. Furthermore, all commercially-available underwater cleaning technologies are either unable to treat niche areas (e.g., underwater jet systems) or are unable to capture and retain all of the biofouling material removed during the treatment process (e.g. rotating brush systems).

SECTION 7

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