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WHITE PAPER

Ship Hull Coating Systems Simplified

How to choose the right ship hull coating system, from an economic and environmental perspective – an executive manual

The Hydrex Group
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UNDERWATER TECHNOLOGY

Part I. Introduction and overview

The steel or aluminum hulls of ships and boats need to be protected from the corrosive effects of water so that they don't rust and fall apart. At the same time, these hulls, and also non-corroding hulls such as those made of glass-reinforced plastic, are prone to accumulating biofouling – marine plants and animals which attach themselves to ship hulls as they do to any suitable underwater surface. In the case of hulls, this fouling can greatly increase resistance and prevent the ship from gliding smoothly through the water. This in turn results in a greater fuel consumption in order to get the vessel from point A to point B and that then causes excessive volumes of emissions of greenhouse gases and other atmospheric pollutants. The biofouling, when it becomes severe, can also damage the coating and the hull itself.

These are the problems inherent in putting ship hulls in the water and keeping them afloat. And they are big problems. Ask any ship owner, operator or technical superintendent. Wrong solutions to these problems can be very costly, as in the case of one shipowner who recently had 70 ships coated with a silicone fouling-release coating only to find out that it was not suitable for the fleet and who is in the process of having the coating removed from all 70 ships and replaced. The cost in terms of drydocking, blasting, preparation and recoating of 70 ships is enormous, especially when one factors in the off-hire time involved and the extra fuel required due to the unworkable hull coating.

The search for ways to protect hulls while eliminating or reducing the effects of biofouling has gone on for centuries, and an uncountable number of attempted solutions have been devised, from covering the hull with copper sheeting, to using arsenic, lead, tin or copper or a variety of other toxic materials to poison the aquatic plant and animal life that tried to settle on the ship's hull, to trying to make the surface so slippery that nothing can attach itself, and many other approaches. One reads of wooden sailing ships being beached and careened (leaned over on one side) so that the fouling could be scraped off. Lack of such maintenance could, in the case of a man of war, lose battles. In fact one of the reasons given for the victory of the British under Nelson at Trafalgar against overwhelming odds was that the ships of Britain's Royal Navy had cleaner hulls and were therefore faster and more agile than those of the French and Spanish. The solutions which were useful on wooden hulls later proved fatal on steel ships due to the galvanic reaction between copper and steel. Times and technology have moved on.

For a number of years the shipping industry thought it had the problem solved when tributyltin (TBT) was found to be most effective in killing fouling. It was used in hull paint for a number of years until it was found that it was extremely toxic to the marine environment in general and that its effects were ecologically disastrous. It has been labelled as the most toxic substance ever introduced by man into the oceans, and was banned from use after much damage had already been done.

We are now in the post-TBT era. Hull protection, maintenance and antifouling are problems for ship designers, builders, owners and operators the world over. The most common hull coatings in use today, antifouling paints based on copper and a variety of other biocides, are considered by most of the industry to be a temporary and undesirable solution, and the search for the perfect hull coating system continues unabated in universities, research centers, and chemistry and biology labs around the world. The volume of literature on the subject is overwhelming.

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Main points to consider

It is a complex problem and there are many factors which must be taken into consideration in devising a hull coating and maintenance system which answers all aspects of the problem for all ships, fleets and offshore structures everywhere.

- Protection of the hull from corrosion, erosion and cavitation, galvanic reactions and anything which threatens its integrity is of primary importance if the ship's hull is to have a long life.

- The coating itself must be long-lasting so that frequent repair or replacement does not keep the ship out of service and add great expense. Ideally it would last the lifetime of the ship.

- Effective management of biofouling is also vitally important since fouling can increase the fuel consumption by 80% or more if allowed to grow unattended, and the increase in fuel consumption brings with it a heavy penalty to the atmospheric environment in terms of added greenhouse gas and other emissions. The biofouling can also threaten the integrity of the coating and the hull if not controlled.

- The substances used to coat the hull must not be harmful to the environment. It is not necessary to keep pouring polluting chemicals into the already polluted oceans. There are non-toxic solutions which are better.

- Another factor which is currently under scrutiny is the subject of invasive species translocated by ships in the form of fouling attached to the hull and to other parts of the underwater ship. Whatever hull coating system is used, it must lend itself to prevention of the spread of non-indigenous, invasive species.

- The hull coating chosen should be able to be cleaned regularly in the water to remove biofouling in its early stages without harmful effects to the coating itself or to the environment. Ideally, effective underwater cleaning of the hull will make it smoother, improving its hydrodynamic qualities and its resistance to biofouling.

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- Ships need to be kept out of drydock as much as possible so that they can be in service, whether for commercial purposes as in cargo and passenger ships, or for operational purposes, as in the case of naval or coast guard vessels. Paint reapplication should never be a prime reason to drydock a vessel.

- All of this must be economically or commercially viable for the shipowner or operator so that the cost of protecting and maintaining a ship's hull and keeping it at optimum performance without environmental damage is not overly expensive.

The best approach to underwater ship hull coating systems will take into account all of these points and score as high as possible on all counts.

This White Paper sets out to examine the available options, not in terms of brand names or manufacturers, but by category and type of coating system, considering the positive and negative aspects of each type.

It is hoped that from this information, shipowners and operators will be able to narrow down their choice of hull coating system and find the one which most benefits their vessel, fleet and circumstances.

Today's choices

There are really only three mainstream categories of hull coating systems available and in use today.

Antifouling (AF)

The one in most general use is biocidal antifouling paint which leaches copper and a number of other biocides into the water in order to kill off fouling that attaches to the ship bottom. These paints gradually release the toxic substances into the water over a period of 3 - 5 years, after which time they become depleted and need to be replaced. They operate on the same principles as did the now banned TBT-based coatings, but use other biocides than compounds of tin as the active ingredients. This type of coating is sold by all the major marine hull coatings manufacturing companies, with variations in the combination of biocides used and the methods by which these are leached into the water. They generally go under the heading of "antifouling paint," "antifoulings" or simply AF.

Fouling-release (FR)

Another category of hull coating system which has increased in popularity is a "non-stick" type of coating which works on the principle that it is difficult for fouling to stick to it in the first place and easy for it to fall off, wash off or "release" when the vessel is under way, especially at speed. Most of the coatings currently available in this category are silicone-based. They do not work on the principle of leaching biocides, and are advertised as being non-toxic and working mechanically rather than chemically. The question of whether or not these coatings really are non-toxic and whether the action is entirely mechanical or also chemical, is examined in this White Paper. While there are a variety of different coatings in this category and not all are silicone-based, they all come under the label of "fouling release coatings" or FR (sometimes FRC).

Hard, inert coatings

A third general category of hull coating systems can be grouped together under the heading of hard, inert, non-toxic coatings. There are a number of subcategories here and these are each examined and compared in this White Paper. They are generally either epoxies, polyesters or vinyl esters; some are reinforced with glass flakes. Variations include ceramic-epoxy. Some come under the heading of Surface Treated Composites (STC) since they can be conditioned underwater with special equipment and their surface improves with routine cleaning. In general these coatings are designed to protect the hull against corrosion and are intended to be used in conjunction with routine cleaning, either using high pressure washing in dry-dock, or underwater cleaning with the vessel still afloat. Routine and timely cleaning keeps the fouling to a minimum and the hull operating at optimum performance. These coatings are non-toxic and do not leach or emit harmful chemicals into the water. A number of different coatings in this category are manufactured by various companies.

This White Paper describes and compares the important features and aspects of the different types of underwater hull coating and maintenance systems available today.

There is an enormous amount of scientific information on the subject of ship hull coatings and marine biofouling. This White Paper is intended to give shipowners and operators and other decision makers in the marine industry a simple, concise overview and economic/environmental comparison on which to base decisions regarding the coating and maintenance of the underwater hulls of their ships or fleets.

Part II. Factors to consider when choosing a hull coating system

It's worth having a closer and more detailed look at the various high level factors which must be taken into consideration when evaluating which coating system to use on a ship, either at newbuild stage or when it comes time to repaint.

1. Protection and longevity

a. ***Will the coating system protect the ship's hull?***

The main purpose for coating the metal underwater hull of a ship is to protect it from corrosion. Uncoated or poorly coated, the underlying metal corrodes. This can be very rapid and destructive. So first and foremost, a hull coating system must protect the hull from corrosion.

I. ***Will the coating system suit the needs of a particular vessel or fleet?***

Different ships, fleets, routes, activities operate under different conditions. When it comes to straightforward hull protection, a coating that might work well for a container vessel sailing in warm or temperate waters and seldom quayside for long, may not be at all suitable for an icebreaker or ice trading cargo vessel, a tugboat or barge that is subject to mechanical rough treatment or a naval vessel which is often moored for months on end and can easily accumulate heavy fouling. So the sailing conditions of the ship have some bearing on the best coating for the hull.

II. ***How thick is the coating? How abrasive resistant? How flexible or brittle? Is it completely impermeable?***

The answers to these questions have much to do with how well the coating will survive under harsh conditions, bumps and scrapes, ice and other challenges.

b. ***How long will the coating last?***

Having established that a particular coating system will provide the necessary protection, the next question is, how long for? Some systems are only designed to last 3 - 5 years before they must be replaced. Others will last the life-time of the ship with only minimal touch-ups. This makes a big difference in total ownership cost of the vessel, when one starts adding up drydocking time, cost of materials and labor, and off-hire time because of the need to repaint.

c. ***Will the coating have to be replaced due to regulations or legislation?***

We have witnessed the enormous work required to comply with the IMO ban on TBT. With current biocidal paints under scrutiny and already subject to regulation, this must be a concern for a shipowner with ships in the newbuild stage or requiring repainting. How safe is it to use a coating which may be banned within the lifespan of that coating?

2. Fuel saving properties and conditions

a. ***How smooth will the hull be after coating?***

Different hull coatings will cause different levels of hull resistance due to skin friction even when no fouling is present. This depends to some degree on the standard of surface preparation and paint application demanded. Nevertheless, different coatings cause more skin friction in themselves than do others. More skin friction means higher fuel consumption. Spread over an entire fleet, an additional 3-4% friction over hydraulically smooth can add up to millions of dollars in extra fuel per year and a heavier carbon footprint for the fleet.

b. ***Will the hull foul (including slime)?***

A more significant factor in fuel saving is marine fouling. This has been covered in earlier White Papers in this series with references to a number of studies done on the subject by researchers dating back to the 1950s. The numbers are significant. The fouling level of a hull has a dramatic impact on how much money a ship or a fleet spends on fuel. The costs involved in dealing with fouling are dwarfed by the potential savings in fuel, with accompanying reduction of GHG emissions. When choosing a hull coating system, a key consideration after basic protection has been established, is how the coating system deals with marine fouling. The three main classes of hull coating systems available each approach the fouling problem in a different way.

The costs involved in dealing with fouling are dwarfed by the potential savings in fuel, with accompanying reduction of GHG emissions.

I. AF coatings attempt to poison the marine animal and plant life so that it does not attach or so that it dies and falls off if it does attach.

II. FR coating systems attempt to present a surface which is difficult for marine life to adhere to or from which it will be easily released when the ship is under way.

III. Hard coatings are susceptible to fouling, and rely on routine cleaning, either underwater or in drydock, for the removal of fouling. In fact none of these coatings prevent slime from attaching. The hull will foul, no matter which of the coating systems is used. And because a thick slime can carry with it a fuel penalty of as much 20%, every effort should be made to handle fouling in its early stages and preferably not allow it to build up even to the level of thick slime and light weed. This brings us to the next factor to consider.

c. ***Is the hull coating suitable for cleaning, in drydock and/or underwater?***

When a shipowner or operator or anyone responsible for the bottom line of a ship or fleet sees how much money can be saved by sailing with a clean hull, free even from slime, then hull cleaning will become a fact of life, as routine as changing the oil in one's car. It therefore becomes important how easy the hull is to clean and whether or not the coating will be damaged or worn away by the cleaning process. Since regular drydocking is not feasible as it is simply too expensive, in-water cleaning is a necessity if a ship is to run at optimum performance and thus avoid heavy fuel penalties. The following points need to be considered:

I. ***Does routine underwater cleaning damage the coating? Can the coating be cleaned without damage to it? Or does the coating improve in***

smoothness with in-water cleaning?

II. ***Will in-water cleaning of the hull pose and environmental hazard, such as a pulse release of biocides, silicone oils or other substances?***

III ***A number of ports and States do not permit in-water cleaning of certain hull coatings such as those coated with biocidal AF paint. Is in-water cleaning avail-able on the planned routes of the ship or ships for which the coating system is being chosen?***

d. ***Is the hull coating suitable for use on ships with lay-up times of any length?***
When the ship is laid up for weeks or months on end, the tendency is for it to foul rapidly, regardless of the hull coating. If the hull coating does not lend itself to cleaning without damage to itself or the environment, including vigorous cleaning of heavier fouling, then it is not suitable for vessels of this type.

3. The need to drydock for repainting

a. ***How often does the coating system require major repair or reapplication?***
This varies with the type of coating and maintenance used and also with sailing conditions. The manufacturer of the coating system will guarantee the life of a particular coating for a period of time. In the case of AF paints this is typically 3 - 5 years, after which the biocides have been used up and at least the AF coatings have to be replaced, if not the underlying corrosion protection scheme. FR coatings tend to damage easily and need extensive and frequent repair. Some hard coatings are expec-ted to last the life of the ship with only minor touch-ups. In this latter case the ship would not have to be drydocked solely because of paint for the life of the ship.

Some hard coatings are expected to last the life of the ship with only minor touch-ups. In this latter case the ship would not have to be drydocked solely because of paint for the life of the ship.

I. ***How many coats need to be applied and how long does this take in drydock?***
This can be a major cost. Surface preparation plus application of paint can vary from five or six days for some coatings to as much as 17 or 18 days for others. This adds up to considerable extra expense in terms of drydock time, labor and off-hire time.

II. ***Does the coating have any special application requirements?***
While all coatings will benefit from thorough surface preparation, some hard coatings require a specific profile (roughness) of the hull in order to adhere fully; this is one of the factors that gives them their tough, long-lasting quality. This usually entails grit blasting. Other coatings not expected to last very long are often applied with less rigorous surface preparation. Some ice coatings have to be applied hot. Another special requirement is the recovery and disposal of toxic waste to be considered in the case of biocidal AF coatings. Regulations are very stringent in many locations.

III. ***How easy is the coating to repair or touch up if it is damaged?***
Some coating systems in current use are made up of five or more different coats for the complete system (e.g. AF and FR coatings both consist of the application of multiple layers of different coating types, including an anti-corrosion scheme which in itself

can consist of several coats, in some cases a tie-coat so that the top coats will adhere, followed by the top coats, whether AF or FR). When these coatings are damaged through to the steel, they must all be reapplied with the necessary curing time in between each coat. This can take time. Other coatings are simpler and can be repaired with one or two coats, some with very short curing times. The ease or difficulty of repairing the coating system when needed will make a difference to time in dry-dock.

4. Environmental concerns

The coating system used on a ship can have a negative impact on the environment. Not all coatings are the same. Therefore the information on which a decision about the coating system to be used is based should include the environmental consequences of its use. This is not just a matter of regulation and legislation which is in flux, but a responsibility to be shared by anyone whose decisions affect the impact of shipping on the environment. Just because something is not illegal does not mean that it is not harmful. In the case of TBT, continued use after its effects were known and before the IMO banned it, caused widespread destruction to the oceans which is still ongoing, long after TBT has ceased to be used.

Just because something is not illegal does not mean that it is not harmful.

a. ***Is the coating system toxic or not toxic to the oceans and waterways?***

In the case of AF coatings, this is an easy question to answer. The AF coating system works on the principle of leaching or gradually emitting poisonous substances into the water to kill off the marine organisms that constitute bio-fouling on the bottom of the ship. In the case of fouling-release coatings, they do not work on this principle and they are presented as non-toxic, but there is evidence that this is not necessarily the case. Silicone oils have been found to have harmful effects on marine life.[1] And experiments conducted at Duke University Marine Lab in Beaufort, North Carolina, USA, have demonstrated that the silicone surface of FR coatings alters enzyme activity in curing barnacle glue, which means that their non-stick function is not simply mechanical but also bio-chemical.[2] There does not seem to be any doubt, however, that the toxic substances such as copper and a variety of herbicides and fungicides leached by AF coatings are more harmful to the environment than FR coatings. Hard coatings tend not to be toxic at all as they are not "active" paints, simply inert protective coatings for the hull.

b. ***Does the in-water cleaning of the coating present any additional environmental hazard?***

In the case of AF coatings, in-water cleaning results in a pulse discharge of an abnormally high level of biocides, and this can raise the concentrations of these biocides in local waters to far more than the usual levels which result from steady leaching of the biocides. This can be hazardous to the port or harbor where the cleaning is being carried out. For this reason, many ports ban in-water cleaning of biocidal AF coatings.

c. ***Does the application or removal of the coating constitute an environmental hazard?***

VOCs (Volatile Organic Compounds)

1. Monika Nendza, "Hazard assessment of silicone oils (polydimethylsiloxanes, PDMS) used in antifouling-/foul-release-products in the marine environment," Marine Pollution Bulletin 54, no. 8 (August 2007): 1190-1196.
2. Daniel Rittschof et al., "Compounds from Silicones Alter Enzyme Activity in Curing Barnacle Glue and Model Enzymes," PLoS ONE, 2011.

emitted by paints and paint solvents can constitute health hazards. Different coatings emit different volumes of VOCs, such as those that do not use a thinner or solvent. There is also the matter of toxic waste. When a toxic coating is blasted off in order for a ship hull to be repainted in part or in whole, the paint particles removed are toxic and must be contained and disposed of safely.

d. ***Does the hull coating system lead to greater fuel efficiency and therefore reduced GHG and other emissions?***
The type of hull coating system chosen can make a big difference to the ship's fuel efficiency. Reduced fuel consumption equates directly to lowered emissions of greenhouse gases and other atmospheric pollutants. It has been argued that the use of non-toxic hull coatings may result in reduced pollution of the oceans but the resulting fouling, unattended, simply increases fuel consumption and atmospheric pollution. However, there are non-toxic coating systems which also result in greatly increased fuel efficiency. So in this case one can have his cake and eat it, fortunately for the environment. One can reduce emissions without pouring biocides into the oceans.

e. ***Does the hull coating system help or inhibit the translocation of hull-borne, non-indigenous, invasive marine species?***
There is great and increasing concern about the effects of translocating, via fouled ship hulls, non-indigenous species (NIS) into aquatic environments where they do not belong and where they can upset the local eco-system and injure local industry and commerce. There are a number of modern examples of this happening. The right hull coating system can help with this situation. While AF coatings may deter invasive species from settling on the hull in the first place, there are a number of species that have built up resistance to the copper and other biocides they contain. This can result in the translocation of species which are biocide immune into areas where the local species are not immune, making a sort of super invasive species which can wreak more havoc.[3] Fouling release coatings do not have this characteristic. They may or may not transport NIS. Those hard coatings which lend themselves to in-water cleaning without damage can be cleaned thoroughly before a fouled vessel sails. Fouling never attaches en route and the ship can therefore arrive at its destination with clean hull and pose minimal NIS threat.

5. Cost

Cost is a vital consideration in choosing a hull coating system for a new ship or for repainting a ship. However, prices per liter of paint can be misleading, as can cost of surface preparation. A poor, inexpensive hull preparation which does not result in an adequate profile, on which cheap paint is applied without too much care may seem very economical compared to a thorough grit blasting which results in a good profile, to which a high quality coating is carefully applied under the watchful eyes of paint inspectors. A comparison of the prices for the above two applications could lead one to choose the cheap solution. However, there

...there are a number of factors which contribute to the real cost of a hull coating system and they must all be taken into account for a total ownership cost assessment.

3. Hall, A. 1981. Copper accumulation in copper tolerant and non-tolerant populations of the marine fouling alga, Ectocarpus siliculosus (Dillwyn) Lyngbye. Botanica Marina 24:223–228.

are a number of factors which contribute to the real cost of a hull coating system and they must all be taken into account for a total ownership cost assessment.

a. ***How much does the paint cost?***
This is fairly straightforward. Some coatings are considerably more expensive than others. But beware of simply looking at price per liter. One should find out what the total cost of materials for coating the entire hull with a particular system will be.

b. ***What surface preparation is required and what does that cost?***
There is a difference between applying coatings to newbuilds and recoating a previously painted ship. Newbuilds are often of modular construction with each module painted and then the modules assembled in the shipyard or fabrication hall, welded together, and then the seams ground down and painted, as opposed to a repaint which is done in drydock on the whole hull. Nevertheless, the cost of surface preparation can be calculated by the coating manufacturer's sales representative.

c. ***How much does it cost to apply the coating?***
As discussed, some hull coating systems require five or more coats with lengthy curing times in between, stretching a full painting job out to as much as 17 days or more. Others can be applied in just two coats with a few hours between coats and can be fully prepared and painted in under a week, ready for launching or relaunching. The costs involved include labor, drydock time and off-hire time.

d. ***How many times can one expect to have to repaint in the ship's lifetime?***
Some coatings are designed to last 3 - 5 years before they need to be replaced. Others are designed to last longer, and a very few will last the full lifetime of the ship. The cost of re-application, including materials, labor, drydock and off-hire costs, need to be figured in when one is estimating total ownership cost of various hull coatings.

e. ***What frequency of in-water cleaning is required for a particular system and how much will this cost?***
Particularly hard, non-toxic coating systems are designed to be cleaned routinely. The cost of in-water cleaning required in order to keep a coating free of any fouling beyond light slime and weed needs to be figured into the overall costs of a particular system.

f. ***How much will the fuel penalty incurred by a particular coating system add to the total ownership cost of hull?***
This is the biggest single cost factor in the entire picture. Not what is spent, but what can be saved with the right hull coating system to suit a specific set of circumstances and needs. The biggest single cost is contained in the fuel penalty. This has been well covered in previous White Papers in this series.

Based on all of these factors, a good estimate can be obtained of how much any hull coating system, maintenance, repair, cleaning, replacement if needed is going to cost for the lifetime of the ship.

It may seem like many different factors to take into consideration, but the exercise is well worth the effort, particularly when considering a new hull coating system for a fleet. The right choice can make a difference of millions, even billions of dollars when projected out for the full lifetime of all the vessels of the fleet.

These different factors are listed below as a checklist of points to be looked at when evaluating and choosing a hull coating system.

Hull Coating Selection Checklist

1. **Protection and longevity**
    a. *Will the coating system protect the ship's hull?*
    b. *Will the coating system suit the needs of a particular vessel or fleet?*
    c. *How thick is the coating? How abrasive resistant? How flexible or brittle? Is it completely impermeable?*
    d. *How long will the coating last?*
    e. *Will the coating have to be replaced due to regulations or legislation?*
2. **Fuel saving properties and conditions**
    a. *How smooth will the hull be after coating?*
    b. *Will the hull foul (including slime)?*
    c. *Is the hull coating suitable for cleaning, in drydock and/or underwater?*
        I. Does routine underwater cleaning damage the coating? Can the coating be cleaned without damage to it? Or does the coating improve in smoothness with in-water cleaning?
        II. Will in-water cleaning of the hull pose and environmental hazard, such as a pulse release of biocides, silicone oils or other substances?
        III. Is in-water cleaning available on the planned routes of the ship or ships for which the coating system is being chosen?
    d. *Is the hull coating suitable for use on ships with lay-up times of any length?*
3. **The need to drydock for repainting**
    a. *How often does the coating system require major repair or reapplication?*
    b. *How many coats need to be applied and how long does this take in drydock?*
    c. *Does the coating have any special application requirements?*
        I. Surface preparation?
        II. Application?
    d. *How easy is the coating to repair or touch up if it is damaged?*
4. **Environmental concerns**
    a. *Is the coating system toxic or not toxic to the oceans and waterways?*
        I. Heavy metals?
        II. Other biocides?
        III. Silicone or fluoropolymer oils?
    b. *Does the in-water cleaning of the coating present any additional environmental hazard?*
    c. *Does the application or removal of the coating constitute an environmental hazard?*
        I. VOCs?
        II. Toxic waste?
    d. *Does the hull coating system lead to greater fuel efficiency and therefore reduced GHG and other emissions?*
    e. *Does the hull coating system help or inhibit the translocation of hull-borne, non-indigenous, invasive marine species?*
5. **Cost**
    a. *How much does the paint cost?*
    b. *What surface preparation is required and what does that cost?*
    c. *How much does it cost to apply the coating?*
    d. *How many times can one expect to have to repaint in the ship's lifetime?*
    e. *What frequency of in-water cleaning is required for a particular system and how much will this cost?*
    f. *How much will the fuel penalty incurred by a particular coating system add to the total ownership cost of hull?*

Part III. The types of hull coatings currently available

In Part I we briefly described the three main categories of underwater ship hull coatings currently available and in use. A more detailed description of each category and its subcategories will be helpful in choosing the best fit for a particular vessel or fleet. This is not a chemical or engineering description but a practical one geared towards the economic and environmental implications more than towards the chemistry and physics involved. These are listed here in order of their prevalence of current use in the existing world fleet.

1. Biocidal antifouling paints (AF).
2. Fouling release "non-stick" coatings (FR).
3. Hard, inert coating systems.

1. Biocidal Antifouling Paints (AF)

To recap, these are hull coating systems designed to control biofouling by emitting poisonous substances to kill the marine plants and animals which constitute fouling, and thus keep them off the ship's hull.

Antifouling coating systems consist of a number of separate coats. This usually includes two anticorrosive coats, the first being a primer if the system is being applied to bare metal; if required, these are followed by a tie coat to ensure adhesion between the anticorrosive coat and the antifouling topcoat; one, two or more antifouling topcoats. This varies from system to system but in all cases at least three and more usually five coats are required.

AF paints are typically rougher than FR coatings and many hard, inert coatings when initially applied, and have an inherent hull friction which is several percentage points higher than hydrodynamically smooth hull. This shows up in an immediate fuel penalty even before any fouling has occurred.

There are three main types of AF paints.

1. Contact leaching paints

This is the simplest and oldest biocidal antifouling. A binder is combined with as much biocide as possible, and the contact of the seawater dissolves the biocide so it is leached into the water. The binder is usually a vinyl or acrylic copolymer and the biocide is usually cuprous oxide. Because the binder is not soluble in water, a leached layer builds up which prevents further release of the biocide, giving this type of coating a very short life.

These are cheap, low end antifouling paints, don't last more than about a year and are not commercially important these days.

2. Controlled depletion polymers (CDP) and soluble matrix or ablative paints

This category includes soluble matrix paints, also referred to as ablative antifoulings. The more modern versions are known as controlled depletion polymers (CDP) to differentiate them from the next category, self-polishing copolymers (SPC). In many cases these terms, CDP and SPC have become marketing terms rather than scientific descriptions and the boundaries between them have become somewhat blurred.

Part of the binder in a CDP is soluble in seawater so that deeper layers are exposed. The paint coating gets thinner and thinner over time as the biocide is leached into the water and the binder dissolves.

The soluble binder used is usually rosin which has a relatively low mechanical strength. The CDP tries to reach a compromise between being soluble enough to attain a sufficient level of leaching, and being strong enough to resist abrasion and damage.

This type of paint is still liable to the formation of a leached layer which then prevents biocides from escaping, rendering the coating ineffective after time and limiting the effectiveness of these coatings to about three years maximum.

3. TBT-free Self-polishing Copolymer (SPC)

The banning of TBT led to the development of tin-free self-polishing copolymers (SPCs). The chemistry of these coatings is not important for the purposes of this paper. There are different variations and different biocides but the principle is that poisonous substances are released into the water to kill potential biofouling. The different binders developed are mainly an attempt to extend the useful life of the coating. The basic principle of a biocide leaching coating remains the same for all the coatings in this category.

There is a chemical reaction between the seawater and the biocides on or near the surface of the paint so that the biocides are released into the water. The surface layer of biocides gradually leaches into the water, allowing the water to react with the next "layer" of biocides which are then released. The leached layers are very thin and can be washed away by the progress of the ship through the water (this is the "self-polishing" aspect–the paint surface which is fairly rough to begin with becomes smoother as the biocide leaches out and the coating wears down), and the process can continue indefinitely, limited only by the initial thickness of the antifouling layers. The fact is that these paints leach heavy amounts of biocide continually and the "self-polishing" name simply refers to the fact that the coating wears away steadily.

Because the leached layer requires a current of water to wash it away so that the next layer can be exposed, these biocidal paints are not effective for vessels which spend some time laid up. This is true of all the AF coatings where a leached layer builds up and remains in place, blocking the escape of more of the biocides.

Again, SPC has become a marketing term more than a technical one, referring to the high end of antifouling paints with a longer life and a higher price sticker.

There is a class of antifouling paints which falls somewhere between the high end SPC and the lower end CDP which is basically an SPC with more rosin in it, making it more soluble. It ranks between CDPs and SPCs in price and in useful lifespan. These are known as hybrid antifouling paints.

Since the AF coatings rely entirely on biocides for their effect, it is worth examining the biocides which have been in general use since the ban on TBT.

Copper

The main biocide in current use in AF paints is copper or some derivative of copper. Studies have been carried out by some of the major paint companies who supply copper-based antifouling paints and by companies who supply copper to those paint companies, stating that copper (and cuprous oxide and other copper based chemicals) are harmless to the aquatic environment.

However, this is in conflict with a large number of independent studies which tell another story. While copper as a trace element in tiny quantities is needed by humans and life forms, it can be highly toxic when in concentration, with a number of health hazards for humans and aquatic life. It is persistent, and the only way to get rid of it in ports and harbors is by dredging which is an extremely cumbersome, onerous and difficult operation.

The evidence available on the effects of copper has already led to a number of laws and regulations forbidding its use in AF paints in certain areas and on certain types of vessels, and also banning the underwater cleaning of ships coated with copper-based AF paints in a number of ports and harbors.

An extensive study of the effects of copper-based antifouling paints carried out by Mridula Srinivasan and Geoffrey Swain at the Department of Marine and Environmental Systems of the Florida Institute of Technology[4] looked at the copper loadings along a 64 km stretch of the east coast of Florida and concluded that:

> Investigations conducted by this study have shown that the use of copper AF coatings on boats and ships in the IRL [Indian River Lagoon] and Port Canaveral, Florida have led to dissolved copper levels that exceed state and federal WQC [Water Quality Certification].

However, is copper an environmentally safe alternative? As shown in previous studies, large quantities of copper in a biologically available form can be toxic to aquatic organisms...

The study also states:

> However, is copper an environmentally safe alternative? As shown in previous studies, large quantities of copper in a biologically available form can be toxic to aquatic organisms (Abbasi and others 1995; Anderson and others 1991; Katranitsas and others 2003; Negri and Heyward 2001). There are also many documented cases of high copper levels (total and dissolved forms) in marine waters around the world, with some exceeding background concentrations or established standard levels (Barber and Trefry 1981; Claisse and Alzieu 1993; Danish EPA 2000; Debourg and others 1993; Hall and others 1988; Madsen and others 1998; Matthiessen and others 1999; Seligman and Zirino 1998; Valkirs and others 1994). Several of these studies found high copper levels in areas close to marinas and harbors and attributed copper-based AF paints to being the source of contamination.
>
> Copper-based AF paints can cause contamination of aquatic systems near marinas in a variety of ways. Most obviously, AF paint prevents the attachment and growth of marine organisms by continually leaching biocides into the water. The rate of release varies depending on paint formulation, age and condition of the paint, and the mode of operation of the vessel. Hull maintenance provides a secondary source of copper contamination; underwater hull cleaning, high-pressure washing of boats, abrasive blasting, hull repair, painting, overspray, and paint spills can all further contribute to copper contamination.

The study calculated that the total annual copper loading into Port Canaveral alone from seven cruise ships for which data was available was over 1.4 tons per year, without counting four other cruise ships and a large number of cargo, military and Coast Guard vessels and other boats which use the port. Copper levels at the port exceed current federal and state standards and therefore pose a

4. Mridula Srinivasan & Geoffrey W. Swain, "Managing the Use of Copper-Based Antifouling Paints," Journal of Environmental Management (2007) 39:423-441

problem.

An independent study conducted by Leigh Taylor Johnson, Marine Advisor and Jamie Anne Miller, Program Representative of the Sea Grant Extension Program/UC Cooperative Extension in San Diego, California, has resulted in extensive findings published on the subject of antifouling paints and the environmental effects of copper. A quote from one of their publications, "What You Need to Know About Nontoxic Antifouling Strategies," follows:

> Why Are Copper-Based Paints a Problem? The most popular bottom paints are pesticides that act by slowly releasing copper. Pleasure craft often spend much time at the slip, so most of the copper in the bottom paint is released there and builds up in waters and sediments. Because metals are elements, they don't degrade over time. Although TBT has been banned for recreational boats in many area, cuprous oxide is still commonly used. Governments in southern California and in Europe are finding that dissolved copper in marina waters has reached toxic levels and that boat bottom paints are major sources of this copper.
>
> Sediments that are contaminated with copper are more expensive to dredge from boat basins, because they require special handling and disposal methods. Boatyards also have high costs for environmental permits and to contain and dispose the copper paint they remove from boat bottoms. These costs are passed on to boaters and marinas.
>
> Dissolved copper levels in boat basins of San Diego Bay and Newport Bay in southern California range from 2.6 to 29.0 parts per billion (ppb), according to the San Diego Regional Water Quality Control Board and the U.S. EPA. The federal and state regulatory standard for dissolved copper is 3.1 ppb (U.S. EPA 2000).
>
> Scientific studies of mussels, oysters, scallops, sea urchins and crustaceans were reviewed to determine how dissolved copper at levels found in southern California marinas affects them. When exposed to dissolved copper at concentrations from 3.0 to 10.0 ppb, various species showed reduced or abnormal: embryo growth, development, swimming and survival; larval growth and survival; adult growth, spawning and survival; and adult digestive, reproductive and muscle tissues (Calabrese et al. 1984; Coglianese and Martin 1981; Gould et al. 1988; Lee and Xu 1984; Lussier et al. 1985; MacDonald et al. 1988; Martin et al. 1981; Redpath 1985; Stromgren and Nielsen 1991). Some of these studies and others (Krishnakumar et al. 1990; Redpath and Davenport 1988) found that many of the above effects became more severe and that feeding, respiration, and waste elimination of adult mussels were also affected at dissolved copper levels from 10.0 to 29.0 ppb.[5]

When exposed to dissolved copper at concentrations from 3.0 to 10.0 ppb, various species showed reduced or abnormal: embryo growth, development, swimming and survival; larval growth and survival; adult growth, spawning and survival; and adult digestive, reproductive and muscle tissues...

Copper and copper derivatives are the most common biocides in use, but they are not the only ones.

Zinc

Another less used metallic biocide used in AF paints is zinc and zinc derived compounds. Tests have shown that both copper and zinc may be toxic to non-target organisms and that the levels of zinc as well as those of copper

5. Leigh Taylor Johnson and Jamie Anne Miller, "What You Need to Know About Nontoxic Antifouling Strategies For Boats," California Sea Grant College Program Report No. T-049, 2000.

need to be considered when evaluating the potential impacts of antifouling paints.[6]

"Booster" Biocides

Because the copper and zinc based antifouling coatings are not as effective as the banned TBT-based coatings they replaced, paint manufacturers have added a number of other biocides into their antifouling coatings in an attempt to make them effective against a broader variety of aquatic species. These include a number of herbicides and fungicides, some of them used in land-based agriculture. These are often referred to as "booster" biocides but this is a misnomer and a euphemism. They are additional biocides in their own right, some of them considered harmful enough to be banned in some areas. They are more accurately referred to as co-biocides.

Diuron, used as a "booster" biocide in AF hull coatings has been entirely banned as an active ingredient in antifouling paints in the UK but is still in use in other parts of the world.

Irgarol 1051, chlorothalomil and Sea-nine 211 (DCOIT) have been banned from use on boats under 25m in length in the UK.

Other European countries including Denmark and Sweden have also banned the use of paints containing Irgarol and Diuron on boats under 25 meters in length.

Irgarol 1051 is a herbicide and was the first of the "booster" biocides to become prominent as an environmental contaminant. Concentrations of the herbicide have been found in ports and marinas around the world and also in fresh water. It is considered to be non-biodegradable.

Sea-nine 211 which is a chemical known as DCOIT, widely used as an additional biocide in AF coatings, has been found to be toxic to non-target species (in other words, species which do not attach to ship hulls as biofouling) and its continued use is discouraged.

Zinc pyrithione, another biocide in use in AF coatings has been found to be more toxic than Irgarol and Sea-nine 211.

To quote one review article from 2003, from which much of the above information has been extracted, "Worldwide occurrence and effects of antifouling paint booster biocides in the aquatic environment: a review," by I. K. Konstantinou and T. A. Albanis:

> Continuous monitoring of biocides concentration profiles in water, sediment and biota is needed to support information that should lead to concerted action to ban or regulate the use of booster biocides. Data are available for the biocides most commonly used in Europe, North America and Japan (Irgarol 1051, Diuron, Sea-nine 211) whilst few or no data are available for other biocides.
>
> …
>
> The need for further research in several vitally important areas such as occurrence, fate and effects of booster biocides is well established by the scientific community, in order to underpin risk assessments and protect environments close to moored vessels. Although the concentration levels of some biocides were not high enough to have acute toxic effects directly on higher species, their chronic effects at low concentrations are unknown and difficult to determine. Gaps in the available data make difficult the evaluation of their impact on the aquatic environment. The precautionary principle

6. Erik Ytreberg, Jenny Karlsson, Britta Eklund, "Comparison of toxicity and release rates of Cu and Zn from anti-fouling paints leached in natural and artificial brackish seawater," Science of the Total Environment, 2010.

should be invoked with respect to the use of booster biocides and provides a good basis on which to formulate policies to the marine environment.[7]

A note on biocides in general

There is broad agreement amongst scientists, researchers, regulatory bodies such as the IMO, environmentalists and others interested in reducing or eliminating ocean pollution that it would be far better if biocides were not used at all in hull coatings.

There is broad agreement amongst scientists, researchers, regulatory bodies such as the IMO, environmentalists and others interested in reducing or eliminating ocean pollution that it would be far better if biocides were not used at all in hull coatings. The question has been, "But what else can we do?" the idea being that biocides are a necessary evil. The fact that the current AF paints may be less harmful than the TBT predecessors, and the argument that failure to use biocidal paints will result in increased fouling which in turn will cause higher fuel consumption along with greenhouse gases and other atmospheric pollution have been thought to mitigate their use. Nevertheless, it has been well documented that excessive levels of copper and the assortment of biocides which go into making an antifouling paint are very harmful to the marine environment and that the full range of their effects is not known. As AF paints increasingly become regulated against and as non-biocidal alternatives have been developed and are in use, the argument in favor of biocidal antifouling coating systems no longer holds any water and the hope is that hull coatings which leach any kind of poisonous substance and thus pose a hazard to sea life, fish, the food chain and humans will entirely disappear from use.

Following is an extract from an article, "Greener Coatings for Cleaner Ships" by Maxim Candries, published in the *Journal of Ocean Technology* in June 2009 which sums up the results of his survey of the environmental concerns regarding biocidal antifouling paints. Maxim Candries is a respected researcher in the field of biofouling and antifouling paints.

<u>The environmental concerns about biocides in antifoulings</u>

Traditional antifouling technology uses coatings that chemically release biocides to kill or retard the growth of fouling. Tributyltin (TBT)-based coatings, which were introduced in the mid-1960s, have for years been the most effective antifoulings due to their acute toxicity to target fouling organisms.

However, severe environmental problems due to the extreme toxicity of TBT have led to a global ban that entered into force in 2008. The toxicity of TBT remains a problem for the foreseeable future since high concentrations of TBT are still being detected in the vicinity of ports and shipyards, particularly in sediments in which TBT has accumulated (Kotrilka, 2009).

Copper-based bottom paints have now become the most widely applied type of antifoulings. They are designed to chemically release copper into surface waters to slow down the growth of fouling organisms. In areas where ships and boats are stationary for al long time such as ports and marinas, copper builds up in the water column and sediments may reach toxic levels. Studies show that dissolved copper at concentrations found in areas such as San Diego affects growth, development, and reproduction of marine life such as mussels, oysters, scallops, sea urchins, and crustaceans.

These species showed reduced or abnormal growth at embryo, larval and adult stage and deficiencies in adult

7. I. K. Konstantinou, T. A. Albanis, "Worldwide occurrence and effects of antifouling paint booster biocides in the aquatic environment: a review, Environmental International, volume 30, issue 2, April 2004, pp. 235-248

digestive, reproductive and muscle tissues (Carson et al., 2009).

In addition, most copper-based antifoulings contain so-called 'booster' biocides to widen the antifouling spectrum. The use of some of these booster biocides has already been banned in certain countries and most of them have come under increased environmental scrutiny (Konstantinou and Albanis, 2004). One method to study the impact of these biocides is by using an environmental risk assessment which factors in the inherent hazard of the biocide and the amount of biocide exposed. In evaluating the environmental effects of dissolved copper or other toxic substances from ship hull coatings, it is important to consider that on top of the leached toxins from biocidal antifoulings, marine life in port and marina waters experience the cumulative effects of other polluting substances such as spilled lubricating oil, diesel, gasoline, cleansers, varnish, garbage, trash, sewage etc. Every reduction of pollution release will therefore help the environment and reducing dissolved copper or other biocide levels will promote a healthier and more abundant food chain for fish, other marine life and birds.

The use of some of these booster biocides has already been banned in certain countries and most of them have come under increased environmental scrutiny...

Regulations worldwide to reduce the released amounts of copper and other biocides are under review in many countries and biocide-free antifouling strategies are considered an effective way to reduce pollution.[8]

The following quote from a 2001 paper by Stefan Nehring gave a warning about the potential environmental effects of copper and the "booster" biocides well before TBT was finally banned:

> In response to first restrictions for TBT application on small boats in the 1980s (Stewart 1996), the use of TBT products was partly superseded by products based on copper. Here, copper compounds such as cuprous oxide (Cu2O), copper thyocyanate (CuSCN) or metallic copper are utilized as the principal biocide predominantly in anti-fouling coatings of pleasure and coastal vessels (Voulvoulis et al. 1999). As since 1992 all applications of TBT antifoulings in Japan have not been allowed, in the meantime approximately 10-20% of the ships of the world trading fleet have TBT-free copper-based self-polishing coatings (Rayner 1999). The lower toxicity of copper compared to TBT causes the necessity of higher amounts of copper to be incorporated in and released from these alternative antifouling coatings in order to warrant sufficient fouling protection (Ranke & Jastorff 2000). However, as a result of this, the copper content of free-living organisms can increase as shown by Caisse & Alzieu (1993) for oysters at the Atlantic coast of France. In order to achieve protection against copper tolerant fouling species, often organic booster biocides ate added. The functional principle of copper and co-biocides in SPC coatings is based on a continuous release at a controlled rate into the seawater, similar to that of TBT. Sucha technological modification may well lessen the environmental problems caused by TBT, but it will throw open new ones, which can be hardly estimated in their range at present. The component copper, actually an essential

8. M. Candries, "Greener Coatings for Cleaner Ships," Journal of Ocean Technology, Vol. IV. No. 3, June 19, 2009.

micro-nutrient for plants, animals and humans, holds many dangers.

Already some time ago, copper was recognized as a risk in drinking water supplies. Chronic increased copper uptake may cause acute poisoning, especially among babies, and can lead to fatal hepatic cirrhosis. Since 1987, thirteen of such deaths have become known in Germany(Otto 1993). It is assumed that copper also has mutagenic and cancerogenic potentials. Since copper is used in many ways (e.g. pipings, gutters), there is a multitude of potential emission sources.

Already at the beginning of the 1990s the copper input into the North Sea from shipping related sources was in the order of 10 to 20% of the total inputs. Today the copper concentration in the German coastal waters reaches a level that causes a significant decrease in the photosynthetic efficiency of microalgae in laboratory tests (Rick et al. 1990). Additionally, a shift in the plankton communities from diatoms to small flagellates is very probable. Such modifications can cause, among others, lasting effects on the whole food chain in the aquatic environment.

It must be noted here that the available knowledge about its ecotoxico-logical relevance in the aquatic environment is absolutely insufficient to issue an environmental label for copper as an anti-fouling agent...

It must be noted here that the available knowledge about its ecotoxicological relevance in the aquatic environment is absolutely insufficient to issue an environmental label for copper as an antifouling agent (Ranke & Jastorff 2000). The same applies to synthetic biocides, such as triazines, diuron and dithiocarbamates, which are added to enhance the effect of copper. These highly toxic additives mainly originate from agricultural sources, where they are used to kill pests and fouling biota (Voulvoulis et al. 1999; Ranke & Jastorff 2000). Nevertheless, there is remarkably little information on their toxicity to marine organisms. As the few available data suggest, they are harmful to micro- and macroalgae, to seagrass and to fish (Peters et al. 1994; Scarlett et al. 1999; Ranke & Jastorff 2000). Laboratory and *in-situ* studies showed that these substances ate highly persistent, so that they pose a chronic threat to the marine environment.

For example, one alternative, the triazine biocide Irgarol® l 1051, has been used in antifoulant paints and already appears to be causing harm (Evans 1999). Irgarol® is a registered trade name of Ciba Specialty Chemicals, Inc. for 2-(tert-butylamino)-4 (cyclopropylamino) -6 (methylthio) -l,3,5-triazine. It has been detected at concentrations approaching acute toxicity thresholds along the coast of England and in the Mediterranean (Readman et al. 1993; Gough et al. 1994; Tolosa et al. 1996; Thomas et al. 2000). Irgarol® also occurs at concentrations high enough to damage microalgal communities off the west coast of Sweden as well as on the German North and Baltic Sea coast (Dahl & Blanck 1996; Biselli et al. 2000).

Therefore, according to present findings, the use of these compounds is not a genuine alternative to TBT. In fact, the OSPAR Working Group on Diffuse Sources has warned that booster biocides in TBT alternatives seem to have the same types of unwanted environmental effects as TBT (Evans 2000). Thus, a considerable topic of the new EC Biocides Directive aforementioned that

> **validated risk assessments of all new biocide products should be carried out in future. Some of the alternatives have already been banned in some countries or some types of craft. For example, Denmark has banned products containing Diuron and Irgarol® and Sweden antifouling paints containing copper and Irgarol® on all pleasure boats on the Swedish east coast. Therefore the application of biocide-free non-stick coatings, e.g. on the base of silicone, seems to be more promising.[9]**

There is a tremendous amount of literature and debate about the environmental effects of copper and co-biocides used in antifouling paint but overall there is plenty of evidence to indicate that these biocides are harmful to the marine environment and the food chain and present a danger to humans as well and that the extent of that danger has not been fully assessed. Similar debate surrounded the use of TBT which prolonged its use for years after it was known to be severely toxic and hazardous, the destructive results of which prolongation continue to this day, long after the biocide was banned.

Antifouling coatings are perceived as being less costly than either Fouling Release coatings or the better hard coatings. Since they are intended to last only 3 - 5 years before replacement, surface preparation is often less meticulous than it would be for a hull coating intended to last the life of the ship. In working out the cost, however, it is important to take into account the total ownership cost for the life of the ship, including the cost of application and reapplication, time in drydock, off-hire time and above all the fuel penalty involved which is the biggest single expense, as well as the long term cost to the environment.

Fouling Release “Non-stick” Coatings

Fouling release coatings are based on the premise that if the surface is slick and sufficiently “non-stick” then it is harder for biofouling to adhere and easier for it to fall off or be washed off by the ship’s motion or cleaned off by cleaning equipment if it does adhere.

The theory of how these surfaces work is not complicated. Since the term “low surface energy” is often used to describe how fouling release coatings work, it is worth explaining the term briefly here.

Two main types of solid surfaces can interact with liquids. Traditionally, solid surfaces have been divided into high energy solids and low energy types. Solids such as metals, glasses, and ceramics, due to their chemical composition have surfaces which require a large input of energy to break, so they are classified as “high energy.” The other type of solids are held together by weak forces and therefore require a low input of energy to break them, and so are referred to as “low energy.” Silicones and fluoropolymers fall into this second category (fluoropolymers are organic polymers such as Teflon which are polymers that contain fluorine; a polymer is a substance defined by its particular chemical structure which forms a variety of synthetic organic materials such as plastics and resins).

This is what is meant by “low surface energy.” The two types of surface behave differently towards liquids, including adhesives. The low surface energy type are harder to wet and harder for adhesives to stick to. Fouling species stick to the ship hull using glues that they exude. A low energy surface is

9. Stefan Nehring, “After the TBT era: alternative anti-fouling paints and their ecological risks,” Senckenbergiana marit., 31 (2) 2001, pages 341-351

harder for them to stick to than a high energy surface.

This is an oversimplified explanation of how FR coatings are said to work but even the complicated explanations involving fracture mechanics do not fully explain the mechanism. Thickness of the coating plays a part as well, and to be effective an FR coating has to be relatively thick. Otherwise the adhering barnacles, for example, cut through to the substrate and the surface fails.

Silicone oils leached by the most commonly used silicone, poly-dimethyl-siloxane (PDMS) are part of the puzzle. Fluoropolymer oils also are also leached into the water to increase the effectiveness of some fouling release coating systems.

These coatings do not work on the basis of leaching biocides as do FR coatings. As such they have been labelled “non-toxic,” “environmentally safe” and “green.”

However, there is more to the picture than this. As stated, some FR coatings such as those containing PDMS do leach silicone oils and these oils, undissolved, can cause physical-mechanical effects with trapping and suffocation of marine organisms[10] ; some have other ingredients which are toxic, in some cases as toxic as TBT.

A recent study shows that some of the silicone FR coatings emit molecules which interfere with the biochemistry of the attaching animal and alter the enzyme activity of the glue exuded.[11] This is no longer merely a “low surface energy” manifestation (where water droplets might be seen to run off a low energy silicone or Teflon surface but thoroughly wet a high energy surface glass windscreen for example). What effects this may have on marine life generally should be carefully explored before labeling the products as non-toxic. Many are not.

The following extract from Chapter 13 by Alistair A. Finnie and David N. Williams, of the 2011 book *Biofouling*, edited by Simon Dürr and Jeremy C. Thomson, describes some of the advantages of FR coating systems over AF coatings, including the current SPCs.

Following the removal of TBT-SPC antifouling paints in the wake of the IMO action (see Chapter 21), silicone FRCs became more commercially attractive in terms of both cost (in comparison to tin-free SPC paints) and application. As technology for overcoating old TBT antifouling paints became available and with further restrictions on the use of biocides, marine paint manufacturers have intensified their research into FRCs that will be effective at lower vessel speeds. A successful outcome of this research has been the introduction in 2007 by International Paint of Intersleek 900, a fluoropolymer-based product which is specified for vessels with speeds of 10 knots and above [82].

A highly significant additional benefit of FRCs over most biocidal antifouling technologies is that they can bring demonstrable economic benefits to the shipowner through the reduction in hydrodynamic drag, arising in large part from the very smooth surface properties of such paint films [83]. Fuel savings of up to 10% have been claimed by some manufacturers [84]. However, opportunities remain for the development of products with even better foul release properties, particularly to microfouling, with the ultimate aim being to produce foul release performance under static conditions suitable for the pleasure craft

Following the removal of TBT-SPC antifouling paints in the wake of the IMO action (see Chapter 21), silicone FRCs became more commercially attractive in terms of both cost (in comparison to tin-free SPC paints) and application.

10. Monika Nendza, “Hazard assessment of silicone oils (polydimethylsiloxanes, PDMS) used in antifouling-/foul-release-products in the marine environment,” Marine Pollution Bulletin 54, no. 8 (August 2007): 1190-1196.
11. Daniel Rittschof et al., “Compounds from Silicones Alter Enzyme Activity in Curing Barnacle Glue and Model Enzymes,” PLoS ONE, 2011.

> **market and delivering even greater fuel savings to the commercial sector. Such products may also have particular benefits in the aquaculture and oil-production/offshore sectors, where the use of biocidal products and/or regular mechanical cleaning still predominate [85,86](see Chapters18 and19).[12]**

Fouling release coating systems usually consist of multiple layers including an epoxy corrosion protection scheme (usually a primer and one or more coats of epoxy), a tie-coat to facilitate the adhesion of the fouling release coating to the epoxy where needed, followed by the fouling release topcoat(s) (silicone or fluoropolymer). There are two main classes of fouling release coating systems:

1. Silicone (the most prevalent)
2. Fluoropolymers.

1. Silicone-based FR coating systems

The most popular fouling release coatings in use are silicone based. Not all silicone-based coatings are the same. For example, there are grades of silicone, with medical grade silicone at the top of the list (this is silicone which is implanted into the human body and therefore must be as non-toxic as possible). There is a notable difference in the adhesion ability of barnacles, for example, to medical grade silicone compared to their ability to adhere to hull coating grades of silicone. Barnacles adhere much more easily to the medical grade silicone than to the lower grades. This data, coupled with the fact that experiments show that silicone surfaces can alter the enzymes in barnacle glue, indicate that there is a toxic biochemical reaction between the silicone and the biofouling, and that the "non-stick" properties of at least some silicone FR coatings are not simply physical-mechanical. Molecules are being emitted from the surface which are having an effect with the living creatures which are attempting to stick to them.

Some silicone FR coatings leach silicone oils into the water. One can see a film on the surface of the water after the coating has been applied and the boat or ship launched. These silicone oils can smother marine organisms other than those which foul ships.

Silicones are very often catalyzed using dibutyltin dilaureate (DBTDL), a cheap catalyst which is as toxic as TBT. When DBTDL is used as a catalyst in silicones, one gram of the final silicone coating contains 215 micrograms of DBTDL. A release of 4 micrograms per square centimeter of coating per day is deadly to settling marine life. This is toxicity. This fact is well known. A materials safety data sheet on a particular brand of DBTL includes the following statement:

> **Risk Statements: Harmful if swallowed. Very toxic by inhalation. Irritating to eyes and skin. Very toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment.**

In general, silicone coatings are hydrodynamically smoother than AF coatings[13]. If kept clean, even of medium to heavy slime, considerable fuel savings over AF coatings can be attained. This can, if properly managed, outweigh the extra cost of the silicone coating system. They tend to be more expensive than FR coatings.

These coatings tend to foul up if the ship is quayside or at anchor for any length of time. If barnacles are permitted to attach and grow on the silicone surface, they can cut through the silicone to the underlying epoxy coats or primer or even the metal hull,

12. Alistair A. Finney, David N. Williams, Chapter 13 "Paint and Coatings Technology for the Control of Marine Fouling," Biofouling, edited by Simon Dürr & Jeremy C. Thompson. Wiley Blackwell, 2010: p 197
13. M. Candries et al. "Report for the EU LIFE Project ECOTEC-STC LIFE06 ENV/B/000362," 2006.

depending on the film thickness of the FR topcoat and the underlying coatings. If this is extensive then the coating will be damaged. Repair is difficult and the answer may be reapplication of the silicone FR system.

FR coatings, as is the case with all current hull coatings, accumulate slime when the vessel is stationary. Some of this slime may be washed off silicone FR coatings if the vessel travels at speed, but enough is left behind to create a significant fuel penalty as covered in detail in *The Slime Factor* white paper in this series.

This, and the fact that any abrasive cleaning of silicone FR coatings damages the coating, has led research into what has been termed "hull grooming:" frequent, light cleaning of the hull using unmanned, low pressure cleaning machines designed to remove fouling while it is still very light without damaging the coating, still in experimental stages at this time. Silicone coatings can be cleaned successfully using low pressure water cleaners in drydock, and the fouling, if light, comes off easily.

While FR coatings appear in general to be more expensive than AF coatings, this must be weighed against the fuel savings that result from a hydrodynamically smoother hull and the lowered impact on the marine environment compared to AF systems. This advantage is lost if the hull is allowed to foul and not cleaned before the fouling gets heavy.

2. Fluoropolymer fouling release coating systems

As defined above, polymers containing fluorine can also be used to create a low energy surface with non-stick properties designed to prevent adhesion of marine fouling. Experiments have shown that fouling adheres less to silicone than to fluoropolymers despite the lower surface energy of the fluoropolymers. Possibly the explanation is contained in the paper cited above regarding the alteration of enzyme activity in barnacle glue as a result of contact with silicone based fouling release coatings.

Initial trials in 1986 were disappointing but the technology has advanced and modern fluoropolymer coatings have had better success (see quote above regarding the advantages of foul release coatings over biocidal antifouling paints).

At this time, the use of fluoropolymers in fouling release coatings is much rarer than the use of silicones.

At least one study is currently in progress regarding any toxicity of fluoropolymers in hull coating systems, and the results will be published when the study is complete.

Hard (Inert) Coatings

There are a number of hard, non-toxic coatings in use. What they have in common is that they are inert, non-biocidal and non-toxic. In order for them to be useful as ship hull coatings they must either be used in waters where marine fouling is not a problem (e.g. ice) or they must be cleaned routinely to keep the hull clean and efficient. Because the coatings are hard, some of them can be cleaned vigorously in the water without being damaged and without the pulse release of biocides which accompanies the in-water cleaning of AF paints, or the damage which can occur when FR coatings are cleaned with abrasive brushes.

Hard coatings do not ablate or gradually dissolve as do AF paints. Nor do they leach oils or molecules of their substance as with many of the FR coatings. They are inert and do not work on the principle of leaching chemicals into the water. From an environmental standpoint they are the safest and least harmful of the coatings currently in use.

The best coatings are extremely tough and hard but also flexible. Some hard coatings are too brittle to survive long, as the ship's hull can flex considerably and the coating needs to flex with it in order to remain firmly attached.

For the purposes of antifouling, hard coatings cannot be considered on their own but only in combination with a workable, economically viable and environmentally safe strategy for cleaning. The expense and inconvenience of frequent drydocking precludes that option, leaving as viable only the various methods of cleaning the hull while the vessel is afloat.

There is a glass flake vinyl ester resin coating which is guaranteed for 10-12 years and expected to last the lifetime of the ship, needing no more than minor touch-ups in drydock if damaged. This type of coating combined with routine cleaning can produce enormous savings in fuel and reapplication costs, which significantly outweigh the cost of initial preparation and coating and of the subsequent routine in-water cleaning.

This hard coating combined with in-water cleaning system has been considered for some time, as shown in this short extract from the book *Advances in marine antifouling coatings and technologies*, Edited by Claire Hellio and Diego Yebra, published in 2009 by Woodhead Publishing Limited:

> Watermann (1999) discusses the option, proposed by David Jones (UMC International, UK), of not applying an antifouling coating at all, but instead applying a hard, smooth anticorrosive system and to maintain it in this condition by regular underwater cleaning for several years. Epoxy, ceramic-epoxy, and glass flake coatings would appear to be likely candidates for such an approach. Watermann and his colleagues determined that special coatings were needed to extend cleaning intervals up to several months. For such a system to be economic, Watermann (1999) considered that sophisticated, possibly robotic, cleaning systems were necessary to support this approach. A network of hull cleaning stations on all important trade routes would also be required, and cleaning would be automatic, either by means of a car wash system or remotely operated vehicle. Even then, awkward areas such as bilge keels, rudders and stern arches would still require manual cleaning.[14]

Perhaps unknown to David Jones and Burkard Watermann, such a coating and cleaning system had already been conceived in 1993 and had been in development stages since 1996, based on a glass flake vinyl ester resin, but using efficient, diver-manned, underwater hull cleaning equipment. This system is currently being used successfully by a major cruise line, a navy, a number of cargo vessels, ferries and other ships. As predicted, the cost of cleaning is more than compensated for by fuel savings and by the fact that the coating does not need to be replaced. Not only does this system last the lifetime of the hull without deteriorating, in fact the surface improves with each in-water cleaning, becoming smoother and less liable to foul.

The car wash system has been tried but so far without success because ship hulls vary so much in size and shape and for other reasons.

A Miami, Florida based company is

14. J. A. Lewis, Chapter 27, "Non-silicone biocide-free antifouling solutions," Advances in marine antifouling coatings and technologies, Edited by Claire Hellio and Diego Yebra, Woodhead Publishing Limited, 2009: 717

working on a remotely operated cleaning system, development of which has been sponsored by the US Office of Naval Research.

Another project along similar lines, the Hull Identification System for Marine Autonomous Robotics (HISMAR), is being funded by the European Commission. It has not developed a commercially successful application yet.

An Australian company has been developing a system of cleaning using heat to kill the marine fouling.

The one system which is available today, practical, workable and industrially viable, uses divers with underwater mechanical cleaning brush machines of various shapes and sizes and different types of rotating brushes.

The main subcategories of hard coating include:

1. Epoxy
2. Glass flake reinforced epoxy or polyester
3. Glass flake reinforced vinylester resin, also known as surface treated composites (STC)
4. Ceramic-epoxy (used on boats and recreational craft at present).

Although these coatings are all included in the category of hard coatings there are considerable differences among them.

1. Epoxy

Epoxy coatings are in widespread use as anti-corrosion protection in both the AF and the FR systems. At least two coats of the biocidal AF paint are usually applied over a primer and two coats of epoxy. The copper in the AF paint must not come in contact with the steel of the hull; otherwise rapid corrosion occurs. Similarly, FR coatings are usually applied over an anticorrosion scheme consisting of an epoxy primer and a second coat of epoxy.

Epoxy coatings are also used on recreation craft. But a pure epoxy coating does not work very well on a ship hull. It tends to be brittle which means that when the hull flexes the epoxy is liable to disbonding – the adhesion is broken. It is also not even as hydrodynamically smooth as a typical AF coating.[15] It is perhaps to overcome these shortcomings that epoxy-ceramic and glass flake reinforcement of epoxy and other hard coatings were developed.

VOC content varies for different types of hard coatings, some quite high, some, such as glass flake vinyl ester resin, very low.

A special case of epoxy coatings are those designed for ice going vessels and icebreakers. These are abrasive resistant coatings with low ice adhesion. They require special hot application and are relatively hard to apply since they "go off" quickly and will not cure at lower temperatures. Epoxy coatings damaged by ice can lead to very rough hulls with consequent high increases in fuel consumption. Experience has shown that a glass flake vinyl ester, surface treated composite makes a better, tougher, more durable coating for ice going vessels or icebreakers. It is also much easier to apply in adverse conditions.[16]

2. Glass flake reinforced epoxy or polyester

These coatings are stronger, more flexible and more long-lasting than the pure epoxy coatings. They can be cleaned underwater without releasing chemicals into the marine environment. The glass flakes enable them to achieve a smoother finish than with pure epoxy coatings and they are tougher.

Their life expectancy is, however, considerably shorter than that of the next category, glass flake vinyl ester resin STC.

15. M. Candries et al. "Report for the EU LIFE Project ECOTEC-STC LIFE06 ENV/B/000362," 2006.

3. Glass flake vinyl ester resin surface treated composite (STC)

Glass reinforced vinyl ester resin coatings have long been used as tank liners. Their use as ship hull coatings is more recent, prevented perhaps due to the higher cost of materials. This is another inert coating which has been tested for toxicity from use, conditioning or underwater cleaning and found to have no toxic effect.[17]

A special formulation of glass flake vinyl ester resin has been used successfully as a ship hull coating for close to ten years. In combination with routine in-water cleaning, this has acquired the term Surface Treated Composite, and has proved very effective in terms of non-toxic hull protection and a system which can achieve great fuel savings when correctly applied and maintained.

The glass flake vinyl ester resin coating is unusual in that in order for it to achieve hydrodynamic smoothness, it needs to be polished or conditioned in the water using specific conditioning tools. This is done soon after launching the newly coated ship. Once this has been done, the coating requires routine cleaning in order to keep it free of fouling. The frequency of the cleaning required varies with the sailing pattern of the vessel and the temperature of the water where the ship is operating.

The glass flake vinyl ester STC is usually applied once in two coats (although this can be increased to three or even four coats under special circumstances), requiring no primer. Curing time in between coats is as little as two or three hours and there is no maximum time for overcoating. The resulting homogenous coat is thick (minimum 1000 microns), very tough and abrasive resistant, and lasts the lifetime of the ship, requiring only minor touch-ups (typically less than 1% of the coated area) during normal scheduled drydocking if any sections are mechanically damaged.

Another unusual property of the glass flake vinyl ester coating is that, unlike all other coatings which deteriorate when cleaned underwater, the STC becomes smoother over time without any significant loss of thickness. It thus becomes more hydrodynamically smooth and less prone to fouling with time and routine cleaning.

Even thick, hard fouling can be completely removed from an STC coated hull leaving no trace of damage from the fouling or the cleaning.

The glass flake vinyl ester STC puts an end to the need for drydocking a ship in order to paint. Any minor touch-ups required can be carried out when the ship is in drydock for usual class inspection, maintenance or repairs without significantly extending the time in drydock.

Its initial application must be properly done, including grit blasting to create a profile of SA 2 ½ (degree of average surface roughness). A rough surface is required for a really strong and long lasting bond to the substrate of any of the coatings described in this paper, but many of these coatings are only intended to last a few years, so the initial preparation is often skimped. With the glass flake vinyl ester resin, this standard of preparation must be insisted upon or the coating will not last the expected life of the ship. The STC is made to last, not designed for frequent (expensive) replacement.

The glass flake reinforced vinyl ester coating is somewhat more expensive than the glass flake reinforced epoxy or polyester coatings but this is more than made up for by its much longer service life, considerably shorter application time and the fuel savings which it makes possible.

16. Personal correspondence with the captain of Swedish icebreaker Oden, 2011.
17. A. Wijga et al., “Biocide free ‘antifouling’ for ships” (translation), 2008.

It should be noted that the glass flake vinyl ester coating is very hard and flexible and therefore remains firmly bonded to the metal or GRP hull even when this is subjected to a great deal of flexing or buffeting as in the case of ice going vessels or icebreakers.

4. Ceramic Epoxy

This is a hard, inert coating intended mainly for boats in sensitive waters. A ceramic-epoxy boat coating has been successfully tested in the San Diego area where the University of California Cooperative Extension has been very active in working to help boat owners replace biocidal AF paint with non-toxic coatings. Whether or not it has application to commercial shipping remains to be seen. The ceramic content strengthens the epoxy, resulting in a longer lasting coating which can be cleaned in the water without any toxic effects.

Another version of the ceramic coating combines ceramics with silicone. It is described as a polymer ceramic/silicone hybrid composite.[18] Again, this coating has been used on boats and recreational craft rather than on ships.

These are the hard coatings which are available and in general use.

No attempt has been made to cover every single coating available. Some are in development or experimental stages and may well become the coating of the future. But these coating systems are the ones in most common use today.

18. Ultraglide Marine, http://www.newceramiccoatings.com.au/ accessed April 2011.

Part IV. Narrowing down the choice

Having listed the various factors that need to be taken into account when choosing a suitable hull coating system for a particular vessel, fleet and set of circumstances, and having looked at the various characteristics and properties of the coating systems available, we can now examine how these go together in practice.

1. Protection and longevity

AF Coatings

Typical AF coating systems tend to be 400-600 microns in overall thickness, easily damaged; scratches and scrapes can go straight through to the steel.

The low end, cheaper coatings and applications will have poorer surface preparation (shot abrasive blasting instead of grit blasting for example, leaving a weaker profile). This will result in poorer adhesion. If the ship hits something, the damage can also lead to undercreep (the rust in the damaged area extends under the paint coatings due to poor adhesion). The more layers of paint are built up, the more stress there is within the coating system, which means that it is likely to break. Repair and recoating will inevitably result in increased hull friction due to the uneven, patchy surface.

The AF coating system is classified as a soft coating. Typically the CDP or SPC antifouling coating will last 3 - 5 years before it must be replaced. These times vary with the type of ship, the coating system used, the surface preparation prior to application, and the waters where the ship operates: for example, if the ship sails in Arctic waters, or if it is a pilot vessel operating in a harbor. These times can be regarded as a general average.

Contact leaching biocidal antifouling coatings typically lose their effectiveness after a year. CDP systems may last three years. And the more expensive SPCs may retain their antifouling properties for as long as 5 years.

When the antifouling properties are depleted, the ship must be drydocked, and the hull coating system repaired where damaged, which requires the full application of all coats to those areas, including replacing the anticorrosion layers. Then the entire hull needs to be repainted with one, two or more coats of biocidal antifouling paint.

This cycle may be repeated once or twice and then the hull will need to be blasted back to bare steel and a whole new system applied. In a 25 year estimated lifespan of the vessel, after the initial AF system has been applied, it is normal for the AF coating to need replacement in drydock 5 - 7 times and the entire system reapplied 2 - 3 times.

Fouling Release Coatings

Typical fouling release coating systems have an overall thickness of 4-500 microns and tend to be very easily damaged. Abrasion resistance is quite poor. Any collision or mechanical abuse of any kind is likely to damage the coating.

Their life cycle and reapplication pattern is similar to that of an SPC. The fouling release coating will need to be reapplied or at least extensively repaired every 3 - 5 years and the entire system will need to be replaced at least once and probably two or three times during the service life of the vessel.

Repairs to FR coatings are more difficult than with AF coatings and hard coatings since they are non-stick coatings and there is invariably an area of overlap when a repair to a smaller area of the hull is required and adhesion is a problem. The fouling release coatings are liable to the same undercreep as the AF coatings, especially when the surface preparation prior to initial application was skimped.

Hard, inert coatings

When it comes to hard coatings, there is a wide distinction between the different types and brands in terms of their protection and longevity properties.

Pure epoxy coatings are not really suitable for ship hull coating on their own, as has been discussed.

In order for hard coatings to have the necessary abrasion resistance and longevity to make them suitable for the topcoat on a ship's hull they need to be reinforced; usually this is done using glass flakes although ceramics have also been used on boats with some success.

Glass flake epoxy and glass flake polyester are hard and impermeable. They can be cleaned underwater without serious damage. They can be expected to last a few years, depending on sailing conditions and type of vessel. However they are more brittle and less flexible than glass flake reinforced vinyl ester resin coatings. This lack of flexibility reduces their toughness and longevity considerably. When the epoxy does crack or damage this tends to go straight down to the steel.

The glass flake reinforced vinyl ester resin using a high proportion of relatively large glass flakes with added ingredients for hardness and adhesion is the best of the hard coatings for all conditions including ice, outperforming the traditional hot sprayed glass reinforced epoxies and polyesters previously normal on icebreakers and ice trading ships.

The glass flake vinyl ester resin surface treated composite will improve rather than suffer from repeated cleaning, becoming more hydrodynamically smooth with each cleaning. This is an extremely tough coating, flexible and able to stick firmly to a hull despite extreme flexing.

This is the only known coating which will last the lifetime of the vessel without need for replacement, requiring only minor touch-ups at drydocking, typically less than 1% of the wetted hull surface area.

Glass flake epoxies, polyesters and vinyl ester coatings have much higher undercreep corrosion resistance than either AF or FR coatings, partly because their standard application requires a more angular, sharper and higher surface profile, such as that produced by grit blasting.

To summarize:

	Protection and longevity
Typical AF coating system(SPC)	Soft coating. Fairly easily damaged. 3 - 5 years before AF coating needs to be replaced. Full recoating down to bare steel 2 or 3 times in 25 years. Not suitable for aluminum hulls.
Typical FR coating system	Soft coating. Easily damaged. 3 - 5 years before FR coat needs repair/reapplication. Full recoating required 1-3 times in 25 years.
Hard coating (glass flake vinyl ester STC)	Tough, flexible. Very corrosion resistant. Lasts lifetime of vessel with only minor touch-ups. No repaint required.

2. Fuel saving properties and conditions

AF coatings

The initial, unfouled AF-coated hull carries with it a fuel penalty of about 2-4% before any fouling has accumulated.[19]

AF coatings can be effective in preventing biofouling beyond the slime (biofilm) and weed stage. They do not usually deter slime. A heavy slime layer can bring about a fuel penalty of as much as 20% compared to a hydrodynamically smooth hull. Copper and co-biocide coating systems do not lend themselves to underwater hull cleaning due to the damage that can occur to the coating, and the environmental harm likely to be caused by a pulse release of biocides. AF coated ships therefore tend to sail with slime, incurring the inevitable extra fuel consumption.

AF coatings can be quite effective in preventing more serious fouling than slime, keeping off barnacles and heavy fouling.

SPCs require that the vessel move through the water for the biocide leach layer to be washed away, exposing a new biocide layer. Therefore vessels with long lay-up times will tend to foul despite the AF coating.

AF coatings can be effective in keeping the fuel penalty down to that incurred by heavy slime or weed, estimated at about 20-34%, preventing the much higher penalty that can come from heavy, hard fouling.

Fouling release coating systems

Towing tank tests carried out to compare the frictional resistance of unfouled hulls coated with an SPC AF coating, a silicone FR coating, an abrasion resistant epoxy for ice going vessels and a glass flake vinyl ester STC showed that the FR coating exhibited considerably less skin friction than the SPC, a similar level to the conditioned STC, the epoxy coating manifesting the highest skin friction. Thus using a third generation or later FR coating can lead to considerable immediate fuel savings when compared to a current generation SPC AF coating system. The glass flake vinyl ester STC becomes hydraulically smoother after routine in-water cleaning and is likely eventually to reach the level of hydraulic smoothness (tests on this are still ongoing).

While work is continuing on a system for cleaning FR coatings in the water without damaging them (Office of Naval Research Hull BUG project working with a Miami based sea robotics company), at this time the only commercially available system for in-water cleaning of fouled FR coatings without damaging them this is underwater high pressure water jet cleaning. However, the equipment is perceived as too expensive and it takes too long to clean a hull with this method for it to be viable. This could change. The EU funded Newcastle University and consortium project HISMAR has worked on a robotic hull cleaner using underwater pressure jets.

A method of killing very light fouling using heat is being developed by an Australian company. Another approach using a system for enveloping the hull as a means of killing the fouling is also in development stages in Australia.

FR coating systems are designed to work best on relatively high activity ships traveling at speeds of 15 knots or more; however, a recent advance has been a fluoropolymer coating designed to work on ships traveling at 10 knots or more.

If a ship has lay-up periods of any length, FR coatings are not suitable as they will foul and barnacles and heavier fouling can cut

19. Schultz, Michael P. (2007) "Effects of coating roughness and biofouling on ship resistance and powering," Biofouling, 23:5, 331 - 341

through the coating. Cleaning an FR coating when it has anything more serious than a biofilm attached is liable to damage the coating.

Some manufacturers are claiming potential fuel savings of 4-10% from using an FR coating instead of an AF paint system.

Hard coatings

A traditional ice going epoxy hard coating demonstrated skin friction marginally greater than that of a modern SPC (both unfouled).

In contrast, a conditioned glass flake vinyl ester hard coating showed considerably less skin friction than the same SPC and only slightly more than a third generation FR coating.

Hard coatings on ships operating in temperate or warm waters are intended to be used in combination with routine underwater hull cleaning to keep the hull free of fouling. Under these conditions, the hard coating without the cleaning is not likely to be a workable approach.

A glass flake vinyl ester STC combined with routine in-water cleaning so that the ship never sails with more than light slime can deliver savings of 10-20% of fuel costs compared to AF or FR system coated ships which will both build up a slime layer. While work is underway on hull “grooming” for FR coatings, this is not currently available commercially. In the case of ships with lay-up times, the hard coating can be cleaned before the vessel sails, so that it sails with a clean hull, thus delivering the savings which, as stated, can be as much as 20% or, in the case of heavy fouling, a lot more.

The glass flake vinyl ester STC is very workable on ships that have lay-up periods *providing the hull is cleaned before the vessel sails*. It is best if the fouling is not allowed to develop beyond slime and weed, but even if it does, it can all be removed without any damage to the STC coating but rather the cleaning results in a smoother surface than before. This system permits very large savings in fuel even on ships that may be laid up for as much as a year before sailing again.

To summarize:

	Protection and longevity	**Fuel saving properties and conditions**
Typical AF coating system (SPC)	Soft coating. Fairly easily damaged. 3 - 5 years before AF coating needs to be replaced. Full recoating down to bare steel 2 or 3 times in 25 years. Not suitable for aluminum hulls.	Unfouled hull roughness from AF coating gives 2 - 4% fuel penalty. Usually sails with slime = up to 20% fuel penalty. Effectively reduces higher fuel penalties.
Typical FR coating system	Soft coating. Easily damaged. 3 - 5 years before FR coat needs repair/reapplication. Full recoating required 1 - 3 times in 25 years.	Smoothest tested surface when unfouled. Usually sails with slime = up to 20% fuel penalty. Can foul badly if vessel has long lay-ups.
Hard coating (glass flake vinyl ester STC)	Tough, flexible. Very corrosion resistant. Lasts life-time of vessel with only minor touch-ups. No repaint required.	Combine hard coating with routine cleaning to provide maximum fuel efficiency. Can save 20% or more on fuel compared to AF or FR coating.

3. The need to drydock for repainting

Under the best of circumstances, putting a ship in drydock for a week or two or longer, or more frequently than absolutely necessary is an expensive, time consuming and disruptive activity. The costs consist of the drydocking fees, labor and material for any work done and most significantly the loss of revenue or service from a vessel being "off-hire" for the duration of the drydock period, whatever the purpose and normal functions of that vessel.

Some drydocking is unavoidable, dictated by the requirements of the classification societies and by the need for some repairs which can only be effected with the ship out of the water. Inspections and maintenance designed to ensure the safety of the vessel, crew and passengers are an essential part of sea travel and transportation.

However, it would be highly advantageous not to have to drydock a vessel or extend time in drydock solely so that the hull can be painted or repainted.

The underwater hull coating system chosen can make a great difference to the amount of time a ship spends in drydock on account of its underwater hull paint.

AF coatings

AF coating systems are designed to last 3 - 5 years on average. The lower end systems can be effective for three years. The higher end SPCs may be effective for five before they wear out. Then the vessel has to be drydocked so that the AF coating can be reapplied after repairs to the anticorrosive scheme have been completed. If this coincides with a scheduled drydocking, then it is a matter of extending the time in drydock by the number of days needed to repair and recoat the hull. Weather conditions can affect the time needed to repaint. If the ship has to be repainted when it is not scheduled for drydocking for other reasons then the entire drydocking must be arranged and carried out solely for the purpose of painting.

Over the lifetime of a ship, taking this as an average of 25 years, 5 - 8 drydockings would be needed solely in order to repaint the hull. Because of the added roughness caused by patching and painting new coats over old, the process of completely removing all paint and blasting the hull back to bare steel will have to be done once, twice, maybe three times in the lifetime of the ship. Usually the AF coating consists of five separate layers, each with a curing time as long as 24 hours. Each patch becomes a weak point in the hull coating. Replacement of the entire AF hull coating system is a more extensive operation and can take as long as 15 - 20 days in drydock. But even repairs where the underlying coats have been damaged and need to be patched are subject to the same curing times and this can add considerably to time in drydock.

If one chooses an AF coating there is no avoiding the requirement to drydock in order to paint or repaint.

FR coatings

Similar rules apply for FR coatings. Some manufacturers claim a longer life before the fouling release coat needs to be replaced and some refer to a "review" of the coat after 5 years.

One manufacturer claims that a fluoropolymer-based FR coating offers greater resistance to a slime build-up than does the more common silicone-based FR coating.

The usual practice is for an FR-coated

vessel to be drydocked every 3 - 5 years. The hull is washed with a low pressure water jet washer which cleans the fouling off quite well. Once the hull is clean, any damage to the soft coating becomes clearly visible, usually in the form of scrapes, scratches and bumps where the ship has collided with something or scraped or bumped the dock, anchor chain or some other structure or object. These coatings are fairly delicate and not abrasive resistant. They are subject to mechanical damage. Where the coating is damaged, it does not release the fouling. As this fouling builds up, the purpose of the coating is defeated.

Repair of an FR coating is more complicated than repair of an AF coating due to the non-stick properties of the FR material making it harder to blend in the repair with the rest of the coating.

After two or three times of repairing the coating system it becomes easier to simply remove the paint down to bare steel and repaint the entire hull. Allowing for curing times and weather, this can take a couple of weeks.

In the lifetime of the vessel it will need to be drydocked 5 - 8 times in order to “review” or replace the fouling release coating in order for this to continue to be effective. The entire system will need to be reapplied from scratch once, twice or three times.

Hard, inert coatings

Information on the service life and need for replacement of many of the hard coatings is not readily available. One manufacturer, however, shows evidence of a glass reinforced polyester ice going ship coating in good condition after five years of sailing in thick ice. In general, the glass flake reinforced hard coatings have the greatest corrosion and abrasion resistance and tend to last.

Glass flake vinyl ester STC hard coating is expected to last the lifetime of the vessel with only minor touch-ups needed (typically less than 1% of the underwater hull surface) when the ship is in drydock routinely as required by class. This expectancy depends on initial standard surface preparation and application, but this is not difficult or complicated. The STC coating is extremely tough and durable while also being flexible. If any mechanical damage occurs it is easily repaired since the 1000 microns dry film thickness (DFT) coating is entirely homogenous. Two coats of the paint are all that is required on bare steel (although three or even four coats can be used for special applications), and the curing time in between coats is 2 - 3 hours. Thus the touch-ups can all be done in a day while the ship is in drydock for other reasons.

This is the only known coating which requires no drydocking specifically for painting for the entire service life of the ship after initial application.

To summarize:

	Protection and longevity	Fuel saving properties and conditions	Need to drydock for repainting
Typical AF coating system (SPC)	Soft coating. Fairly easily damaged. 3 - 5 years before AF coating needs to be replaced. Full recoating down to bare steel 2 or 3 times in 25 years. Not suitable for aluminum hulls.	Unfouled hull roughness from AF coating gives 2 - 4% fuel penalty. Usually sails with slime = up to 20% fuel penalty. Effectively reduces higher fuel penalties.	5 - 8 drydockings required for paint alone during ship's service life including 1 - 3 full blasting and repainting. Multiple coats and lengthy curing times can mean 2 - 3 weeks in drydock for a full repaint.
Typical FR coating system	Soft coating. Easily damaged. 3 - 5 years before FR coat needs repair/reapplication. Full recoating required 1 - 3 times in 25 years.	Smoothest tested surface when unfouled. Usually sails with slime = up to 20% fuel penalty. Can foul badly if vessel has long lay-ups.	5 - 8 drydockings required for paint alone during ship's service life including 1 - 3 full blasting and repainting. Multiple coats and lengthy curing times can mean as much as 2 - 3 weeks in drydock for a full repaint.
Hard coating (glass flake vinyl ester STC)	Tough, flexible. Very corrosion resistant. Lasts life-time of vessel with only minor touch-ups. No repaint required.	Combine hard coating with routine cleaning to provide maximum fuel efficiency. Can save 20% or more on fuel compared to AF or FR coating.	Applied once to a hull. No need to repaint beyond minor touch-ups during routine drydocking. Usually applied in 2 homogenous coats with 2 - 3 hours minimum and no maximum in between coats.

4. Environmental concerns

There are a number of ways that the chosen hull coating can increase or decrease the ship's impact on the environment. These are, in essence,

- chemical pollution of the marine environment during application, use or cleaning of the coating
- atmospheric pollution in the application of the coating by VOCs (volatile organic compounds) in the solvents
- the hull coating system can result in increased or decreased fuel consumption which leads to an increase or decrease in the emission of greenhouse gases and other contributors to atmospheric pollution
- the hull coating system can contribute to the spread of invasive non-indigenous species or can prevent that spread.

Each coating type rates differently on each of these points.

AF coatings

While the ingredients and proportions and the method of release of biocide vary from one AF coating system to the next, they all have one thing in common: they work by releasing poisonous chemicals into the water. We have already covered the different biocides and their effects in Parts I and III of this paper. All AF coatings in use today emit poisonous chemicals into the water and these chemicals are in varying degree harmful to marine life, contaminate the environment and the food chain, and are hazardous to humans.

This environmental pollution occurs constantly while the AF coating is effective, the biocides leaching into the water whether the ship is at anchor or moored or sailing. It occurs in pulse release form if the AF coated hull is cleaned while the ship is afloat. No filter system yet devised has shown that it can collect all the biocides emitted during hull cleaning of an AF coating – certainly not in an economically feasible way. The pollution can also occur as a result of run-offs if the hull is pressure washed or high pressure stripped in drydock and the hazardous waste is not entirely collected and disposed of properly.

VOC levels of a typical SPC are more than those of typical silicone FR coating system which in turn are three times as high as a glass flake vinyl ester STC.

Compared to no fouling control whatever, an AF coating which is effective in deterring or killing macrofouling organisms, will prevent the huge fuel penalty which accompanies heavy fouling. This will result in lower fuel consumption than that of a vessel with heavy fouling. This in turn lowers GHG emissions and other atmospheric pollutants compared to a ship with a badly fouled hull.

However, AF coatings tend not to be effective in preventing a slime layer from building up. Since slime can carry a 20% fuel penalty, the AF coating system does not perform so well compared to one which could maintain, for example, a fouling level of light slime or less. AF coatings tend to be rougher than fouling release coatings or conditioned glass flake vinyl ester hard coatings for example so that even without fouling present the AF coating is increasing the hull friction by several percent compared to a hydraulically smooth hull.

On the subject of non-indigenous species, AF coatings get a mixed review. Obviously if they kill or deter marine life it won't attach to the hull and therefore will not be translocated. However, there is growing evidence that there are species which are immune or develop immunity to the biocides in the AF coatings and when translocated these species have a competitive advantage over the aquatic species in their new home which are not so immune, and so can invade with greater chance of success.[20]

Overall, the AF coatings score worst of all the available hull coatings on the environmental safety scorecard, which is why they have been subject to increasing legislation and regulation and soon may not be tolerated at all.

FR coatings

The general impression conveyed by manufacturers in their literature and advertising is that fouling release coatings are not toxic. As covered in Part I and III of this White Paper and in other White Papers in this series, it is safer and more accurate to say that silicone and fluoropolymer fouling release coatings do not work on the principle of controlling fouling by leaching biocides into the water. However, most of the FR coatings do leach oils into the water, and these oils can have a harmful effect on aquatic life and non-target species. As discussed, tests have shown that a silicone coating will alter the enzymes in curing barnacle glue. There is also the fact that in silicone FR coatings the catalyst used

20. Jamie Gonzalez & Leigh Taylor Johnson, "Copper-Tolerant Hull-Borne Invasive Species: Further Analysis, Sea Grant, 2008

is the highly toxic dibutyltin laurate which is as harmful as TBT and is present in highly toxic proportion in the coating.

It is therefore inaccurate to describe FR coatings in general as non-toxic or environmentally safe. At the very least it must be stated that the full environmental impact of silicone and fluoropolymer fouling release coatings has not been established and needs to be fully investigated. The consequences of greatly increased market share will only be known if that market share is achieved, but the data published so far indicates that undissolved silicone and fluoropolymer oils can smother marine life, that silicone coatings interfere with the enzymes in barnacle glue, that the cheapest and most prevalent silicone catalyst is as toxic as TBT. The broader environmental consequences at least merit further study.

Underwater cleaning of FR coatings is a delicate affair. Toxicity tests of the water before and after cleaning need to be done to establish whether or not underwater cleaning of FR coatings poses any environmental threat. The same is true for the run-off water when FR coatings are pressure washed in drydock.

At least some brands of silicone coating have lower VOC content than AF coatings so can be considered more environmentally benign in that regard.

An FR coating, unfouled, is hydrodynamically smoother than an AF coating in the same condition. This means a lower fuel penalty. As with any other hull coating, slime accumulates almost immediately when the hull is immersed. It is possible that heavier slime will partially wash off when the ship is in motion, especially at higher speeds. However, some slime will remain and will then transform into weed fouling even during sailing. Some manufacturers claim fuel savings of between 5 and 10% through use of their FR coating compared to AF coatings. If these figures are accurate, then the FR coating will lower fuel consumption and therefore GHG and other emissions.

For a high activity, higher speed vessel, it is unlikely that serious fouling will accumulate on the hull and therefore the NIS issue will not materialize with FR coatings under these conditions. The potential problem arises when the vessel remains in port or at anchor for an extended period and fouling is permitted to build up. Such fouling may or may not wash off when the ship does sail. It depends if the fouling species have dug through the FR coating to the underlying anticorrosive scheme or to bare steel. If they have, then the likelihood of their washing off is low. Thus non-indigenous species might be translocated.

Hard, inert coatings

Since hard, inert coatings are of little use in temperate or warm waters if not combined with a program of routine in-water hull inspection and cleaning, the entire system of coating plus maintenance must be considered, not just the coating.

These coatings are hard, inert and by their very nature free of biocides. While the toxicity of each coating needs to be evaluated separately, there is no evidence that epoxy or polyester or vinyl ester coatings are toxic. Tests done on glass flake vinyl ester STC showed it to be entirely non-toxic to the marine environment when in use, or when conditioned or cleaned in the water.

VOC content of the glass flake vinyl ester STC is less than a third of that of a low VOC content silicone coating and less than a fifth of that of a typical AF coating.

Of the three major classes, hard coating systems and in particular glass flake vinyl ester resin, offer the best fuel savings and therefore lowest fuel consumption and GHG emission. In the case of vinyl ester resin, because it can be cleaned as often as required in the water with no adverse effects to the coating, but on the contrary showing better hydraulic smoothness with routine cleanings, the hull can be kept at a level of fouling no more severe than light slime at all times and ships which have been stationary for some time can be fully cleaned in the water before they sail. Sailing with such a hull when it is kept clean can reduce fuel consumption by 20%, thus reducing GHG and other emissions by a similar factor.

The best way to ensure that non-indigenous species are not translocated via ship hulls is to make sure that those ship hulls are free of fouling before they sail. A thorough cleaning of the hull including various niche areas favored by NIS will avoid such issues and save a great deal on fuel consumption and therefore GHG and other emissions at the same time.

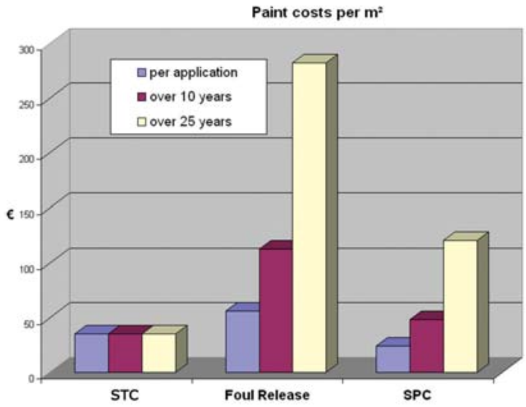
To summarize:

	Protection and longevity	**Fuel saving properties and conditions**	**Need to drydock for repainting**	**Environmental concerns**
Typical AF coating system (SPC)	Soft coating. Fairly easily damaged. 3 - 5 years before AF coating needs to be replaced. Full recoating down to bare steel 2 or 3 times in 25 years. Not suitable for aluminum hulls.	Unfouled hull roughness from AF coating gives 2 - 4% fuel penalty. Usually sails with slime = up to 20% fuel penalty. Effectively reduces higher fuel penalties.	5 - 8 drydockings required for paint alone during ship's service life including 1 - 3 full blasting and repainting. Multiple coats and lengthy curing times can mean 2 - 3 weeks in drydock for a full repaint.	Contaminates marine environment with toxic biocides, harming marine life, the food chain and humans. Pulse release of biocides if cleaned in-water. High VOC content when applied. Limits fuel consumption and GHG emissions from effects of heavy fouling. Prevents some NIS but furthers others.
Typical FR coating system	Soft coating. Easily damaged. 3 - 5 years before FR coat needs repair/reapplication. Full recoating required 1 - 3 times in 25 years.	Smoothest tested surface when unfouled. Usually sails with slime = up to 20% fuel penalty. Can foul badly if vessel has long lay-ups.	5 - 8 drydockings required for paint alone during ship's service life including 1 - 3 full blasting and repainting. Multiple coats and lengthy curing times can mean as much as 2 - 3 weeks in drydock for a full repaint.	Does not contain biocides but leaches potentially harmful oils, alters enzymes in barnacle glue; some silicones catalyzed by highly toxic dibutyltin laurate. Medium VOC. Some reduction in fuel consumption/GHGC an help limit spread of NIS.
Hard coating (glass flake vinyl ester STC)	Tough, flexible. Very corrosion resistant. Lasts life-time of vessel with only minor touch-ups. No repaint required.	Combine hard coating with routine cleaning to provide maximum fuel efficiency. Can save 20% or more on fuel compared to AF or FR coating.	Applied once to a hull. No need to repaint beyond minor touch-ups during routine drydocking. Usually applied in 2 homogenous coats with 2 - 3 hours minimum and no maximum in between coats.	Non-toxic in use, conditioning and cleaning. Low VOC. Combined with cleaning gives lowest fuel consumption/ GHG emissions. Cleaning before ships sail prevents spread of NIS.

5. Cost

Various costs have to be considered before one can arrive at a useful comparison in terms of overall financial impact of a particular hull coating system. There is the initial cost of surface preparation and application, the cost of maintenance and reinstallation throughout the service life of the ship including time in drydock and the consequent off-hire time, and there is the potential savings in fuel costs attainable. From a financial standpoint, the best hull coating system will save far more in fuel and other costs than its own cost of application and maintenance. When comparing coating systems from an economic viewpoint, the entire life cycle of the ship and the cost of fuel must all be considered.

The following two graphs give a quick, overall comparison of how this breaks down for the three main classes of underwater hull coatings. [21]



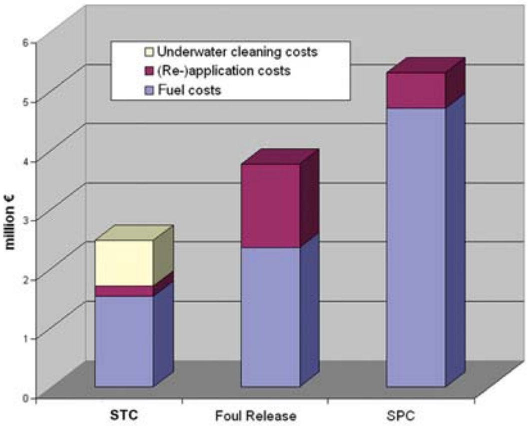
The first graph compares paint costs the different coating types for a single application, over a 10 year period and over a 25 year period.

Full hull coating systems comparison table

	Protection and longevity	Fuel saving properties and conditions
Typical AF coating system (SPC)	Soft coating. Fairly easily damaged. 3 - 5 years before AF coating needs to be replaced. Full recoating down to bare steel 2 or 3 times in 25 years. Not suitable for aluminum hulls.	Unfouled hull roughness from AF coating gives 2 - 4% fuel penalty. Usually sails with slime = up to 20% fuel penalty. Effectively reduces higher fuel penalties.
Typical FR coating system	Soft coating. Easily damaged. 3 - 5 years before FR coat needs repair/reapplication. Full recoating required 1 - 3 times in 25 years.	Smoothest tested surface when unfouled. Usually sails with slime = up to 20% fuel penalty. Can foul badly if vessel has long lay-ups.
Hard coating (glass flake vinyl ester STC)	Tough, flexible. Very corrosion resistant. Lasts lifetime of vessel with only minor touch-ups. No repaint required.	Combine hard coating with routine cleaning to provide maximum fuel efficiency. Can save 20% or more on fuel compared to AF or FR coating.

21. EU LIFE Project ECOTEC-STC LIFE06 ENV/B/000362 ECOTEC-STC: Evaluation of a biocide-free hull protection and antifouling system with environmental and economical benefits Layman's Report

The second graph compares the total ownership cost for the three main categories of hull coating systems, including application and reapplication costs, underwater cleaning costs and the fuel costs over 25 years.



When all the costs aspects are taken together, it is estimated that the overall economical impact of [the glass flake vinyl ester STC] is less than half of that of an SPC and about 2/3 of a foul release for a 1000-TEU container vessel over 25 years.[22]

As the graph shows, this equates to a savings of over 1.5 million EUR (2.15 million USD) for the foul release coating compared to the SPC and a savings of about 3 million EUR (4.3 million USD) for the STC compared to the SPC AF coating and about 1.5 million EUR (2.15 million USD) for the STC compared to the FR coating. If this is spread across many vessels or even the entire international fleet, the savings that can be realized from choosing the right hull coating system are enormous. At current bunker fuel costs, the figures in 2011 are far higher than shown in this 2006 study.

Need to drydock for repainting	Environmental concerns	Cost
5 - 8 drydockings required for paint alone during ship's service life including 1 - 3 full blasting and repainting. Multiple coats and lengthy curing times can mean 2 - 3 weeks in drydock for a full repaint.	Contaminates marine environment with toxic biocides, harming marine life, the food chain and humans. Pulse release of biocides if cleaned in-water. High VOC content when applied. Limits fuel consumption and GHG emissions from effects of heavy fouling. Prevents some NIS but furthers others.	Overall cost including application and reapplication, maintenance and additional fuel consumption is twice that of the vinyl ester STC and about 1/3rd more than that of an FR coating. Initial application is cheaper than either of the other options.
5 - 8 drydockings required for paint alone during ship's service life including 1 - 3 full blasting and repainting. Multiple coats and lengthy curing times can mean as much as 2 - 3 weeks in drydock for a full repaint.	Does not contain biocides but leaches potentially harmful oils, alters enzymes in barnacle glue; some silicones catalyzed by highly toxic dibutyltin laurate. Medium VOC. Some reduction in fuel consumption/GHG. Can help limit spread of NIS.	Overall cost including application and reapplication, maintenance and improved fuel consumption is one and a half times that of the vinyl ester STC and about 2/3rd that of an AF coating. Initial application is the highest of all three.
Applied once to a hull. No need to repaint beyond minor touch-ups during routine drydocking. Usually applied in 2 homogenous coats with 2 - 3 hours minimum and no maximum in between coats.	Non-toxic in use, conditioning and cleaning. Low VOC. Combined with cleaning gives lowest fuel consumption/GHG emission. Cleaned before ships sail prevents spread of NIS.	Overall cost including application, maintenance and fuel savings is half that of an AF and about 2/3rd that of an FR coating. Initial application is higher than AF, lower than FR. Cleaning costs are included.

22. Ibid.

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